

# 1 Title

2 Areas of global importance for terrestrial biodiversity, carbon, and water

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## 64 **Summary paragraph**

65

66 To meet the ambitious objectives of biodiversity and climate conventions, countries and the  
67 international community require clarity on how these objectives can be operationalized spatially,  
68 and multiple targets be pursued concurrently<sup>1</sup>. To support governments and political conventions,  
69 spatial guidance is needed to identify which areas should be managed for conservation to generate  
70 the greatest synergies between biodiversity and nature's contribution to people (NCP). Here we  
71 present results from a joint optimization that maximizes improvements in species conservation  
72 status, carbon retention and water provisioning and rank terrestrial conservation priorities globally.  
73 We found that, selecting the top-ranked 30% (respectively 50%) of areas would conserve 62.4%  
74 (86.8%) of the estimated total carbon stock and 67.8% (90.7%) of all clean water provisioning, in  
75 addition to improving the conservation status for 69.7% (83.8%) of all species considered. If  
76 priority was given to biodiversity only, managing 30% of optimally located land area for  
77 conservation may be sufficient to improve the conservation status of 86.3% of plant and vertebrate  
78 species on Earth. Our results provide a global baseline on where land could be managed for  
79 conservation. We discuss how such a spatial prioritisation framework can support the  
80 implementation of the biodiversity and climate conventions.

81

82

## 83 **Introduction**

84

85 Biodiversity and nature's contributions to people (NCP) are in peril, requiring an increasing level  
86 of ambition to avert further decline<sup>1</sup>. Existing global biodiversity conservation targets are unlikely  
87 to be met by the end of 2020<sup>2</sup>. Similarly, the world is falling short of mobilizing the full climate  
88 mitigation potential of nature-based climate solutions, estimated at around a third of mitigation  
89 effort under the Paris Agreement<sup>3</sup>. A new global biodiversity framework is scheduled to be adopted  
90 by the Convention on Biological Diversity (CBD) in Kunming, China, in October 2020<sup>4</sup>, and there  
91 are growing calls to integrate nature-based solutions into climate strategies<sup>5</sup>.

92

93 Targets for site-based conservation actions, hereafter area-based conservation targets, will  
94 likely remain important for the new global biodiversity framework<sup>4</sup>. Several calls have been made  
95 for such targets, including suggestions that at least 30% of land and oceans be protected for  
96 conservation and an additional 20% for climate mitigation<sup>6</sup> and that the value of areas of global  
importance for conservation is maintained or restored<sup>7</sup>. The Sustainable Development Goals

97 (SDGs), the United Nations Framework Convention on Climate Change (UNFCCC) and the CBD  
98 emphasize that habitat conservation and restoration should contribute simultaneously to  
99 biodiversity conservation and climate change mitigation<sup>4</sup>. Recent analyses of conservation  
100 priorities for biodiversity and carbon have spatially overlaid areas of importance for both assets,  
101 effectively treating the two goals as to be pursued separately (e.g.<sup>6,9</sup>). However, multi-criteria  
102 spatial optimization approaches applied to conservation and restoration prioritisation have shown  
103 that carbon sequestration could be doubled, and the number of extinctions prevented tripled, if  
104 priority areas were jointly identified rather than independently<sup>10,11</sup>. Yet, no comparable  
105 optimization analyses exist at a global scale.

106 A number of recent studies have attempted to map spatial conservation priorities on land<sup>12</sup>,  
107 relying on spatial conservation prioritisation (SCP) methods<sup>13–1617</sup>. However, these approaches are  
108 limited, in that: they (*i*) are limited by geographic extent<sup>22</sup> or focus on only a subset of global  
109 biodiversity, notably ignoring either reptiles or plant species, which show considerable variation  
110 in areas of importance compared to other taxa<sup>18,19</sup>; (*ii*) focus on species representation only, rather  
111 than reducing extinction risk, as per international biodiversity targets, and often ignore other  
112 dimensions of biodiversity, e.g. evolutionary distinctiveness<sup>20,21</sup>; (*iii*) do not investigate the extent  
113 to which synergies between biodiversity and NCPs, such as carbon sequestration or clean water  
114 provisioning<sup>22</sup>, can be maximised<sup>21</sup>; and (*iv*) they use a-priori defined, and subjective measures of  
115 importance, such as intactness<sup>8,17</sup>, or area-based conservation targets, such as 30% or 50% of the  
116 Earth<sup>6,24</sup> instead of objectively delineating the relative importance of biodiversity and NCPs across  
117 the whole world irrespective of such constraints.

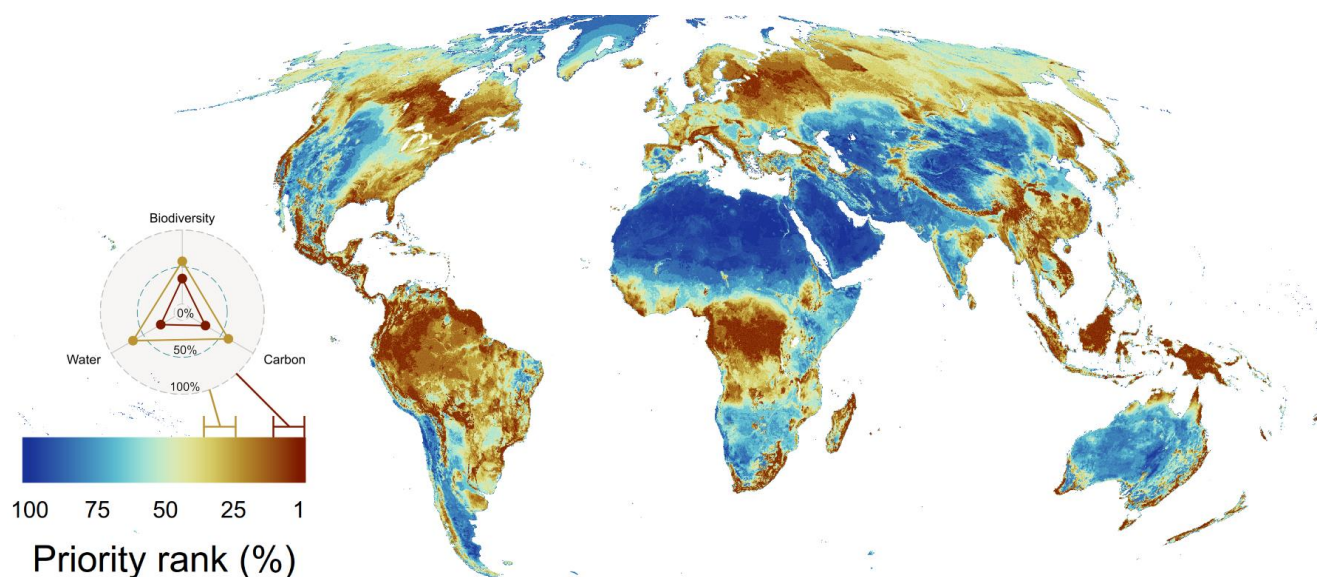
118 The aim of this study is to identify the most important areas for biodiversity - here focussing  
119 on species conservation - as well as NCPs including carbon storage and water provisioning, to be  
120 managed for conservation globally. We define managing an area for conservation as any site-based  
121 action that is appropriate for the local context (considering pressures, tenure, land-use, etc.), and  
122 that is commensurate with retaining or restoring the desirable assets (e.g. species, habitat types,  
123 soil or biomass carbon, clean water). This management may sometimes require legal protection to  
124 be effective, but not necessarily in the form of protected areas.

125 We obtained fine-scale distribution maps for the world's terrestrial vertebrates as well as  
126 the largest sample of plant distribution data ever considered in global species-level analysis, ~41%  
127 of all accepted species names in this group. As NCPs we use the latest global spatial data on above-  
128 and below-ground biomass carbon, and vulnerable soil carbon, as well as the volume of potential  
129 clean water by river basin. We applied a multicriteria spatial optimization framework to investigate  
130 synergies between these assets and explore how priority ranks change depending on how much  
131 weight is given to either carbon sequestration, water provisioning or biodiversity, and examined  
132 whether priorities vary if species evolutionary distinctiveness and threat status are considered.  
133

## 134 **Results**

135 We found large potential synergies between managing land for biodiversity conservation, storing  
136 soil and biomass carbon, and maintaining clean water provisioning. Managing the top-ranked 10%  
137 of land, i.e. those areas with the highest priority, to achieve these objectives simultaneously (Fig.

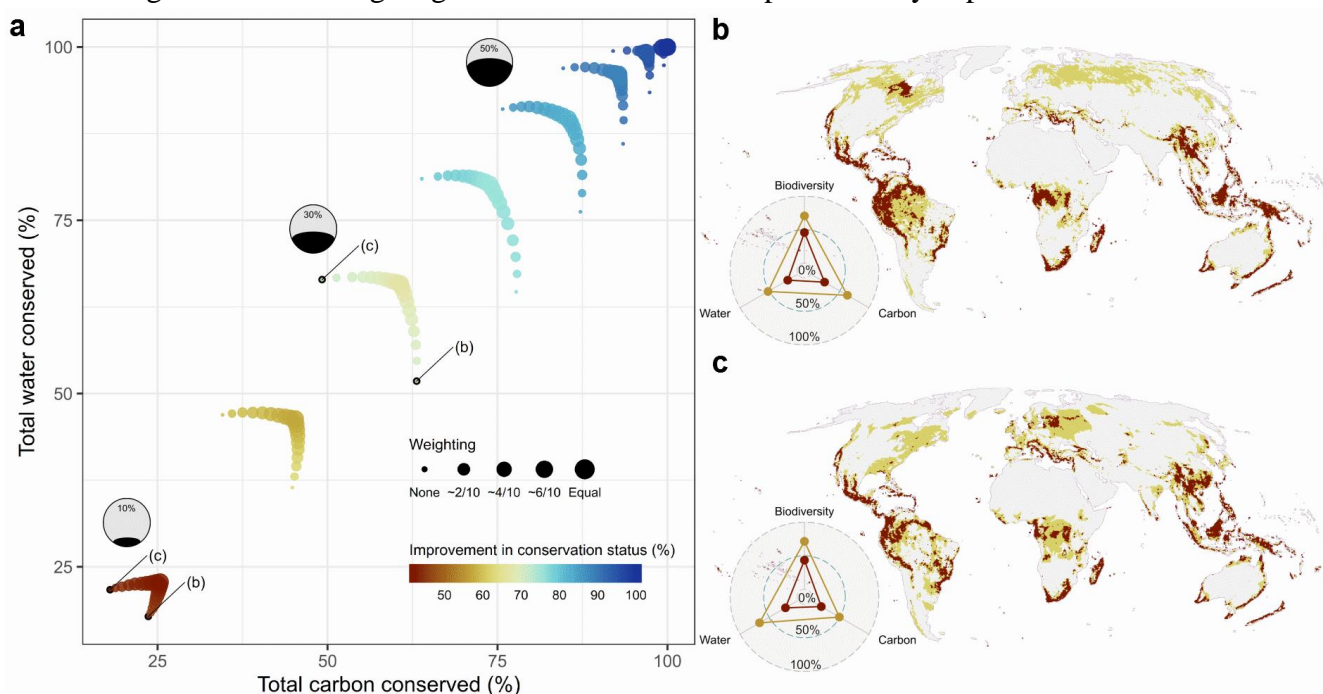
138 1, SI Fig. 1), has the potential to improve the conservation status of 46.1% of all species considered,  
139 of which 51.1% are plant species, as well as conserve 27.1% of the total carbon and 24.1% of the  
140 potential clean water globally. Areas of biodiversity importance notably include mountain ranges  
141 of the world, large parts of Mediterranean biomes and South-East Asia (SI Fig. 2) and were overall  
142 mostly comparable to previous expert-based delineations of conservation hotspots<sup>16</sup>, while also  
143 highlighting additional areas of importance for biodiversity only, such as the West African Coast,  
144 Papua New-Guinea and East Australian Rainforest (SI Fig. 2). The Hudson Bay area, the Congo  
145 Basin and Papua New Guinea were among the top-ranked 10% areas for global carbon storage (SI  
146 Fig. 3a), while the Eastern United States of America, the Congo, European Russia and Eastern  
147 India were among the areas with the greatest importance for clean water provisioning (SI Fig. 3b).  
148 Overall, top-ranked areas of joint importance of biodiversity, carbon and water were spatially  
149 distributed across all continents, latitudes and biomes.  
150



152 **Fig. 1: Global areas of importance for terrestrial biodiversity, carbon and water.** All assets  
153 were jointly optimized with equal weighting given to each asset (central point in the series of  
154 segments in Fig. 2) and ranked by the most (1-10%) to least (90-100%) important areas to conserve  
155 globally. The triangle plot shows the extent to which protecting the top-ranked 10% and 30% of  
156 land (dark brown and yellow areas on the map) contributes to improving species conservation  
157 status, storing carbon and providing clean water. The map is at 10 km resolution in Mollweide  
158 projection. A map highlighting the uncertainty in priority ranks can be found in SI Fig 1.  
159

160 Synergies and trade-offs depend on the relative importance given to conservation of  
161 terrestrial biodiversity, carbon storage and water provisioning (Fig. 2a). We explored an array of  
162 conservation scenarios each with a range of possible outcomes: at one extreme, priority is given  
163 to conserving biodiversity and carbon only, and with equal weight (Fig. 2b). At the other extreme  
164 are scenarios that prioritize conserving only biodiversity and water (Fig. 2c). Intermediate options  
165 include giving equal weighting to all three assets (Fig. 1). Similar to earlier assessments<sup>9,26,27</sup>, we  
166 found synergies between the conservation of biodiversity and carbon storage (Fig. 2b). However

167 we also discovered similar synergies for biodiversity and water provisioning (Fig. 2c). Conserving  
168 the top-ranked 10% of land for biodiversity and carbon can only protect up to 23.6% of the global  
169 total carbon and 45.8% of all species (Fig 2a), while maintaining 17.8% of all global water  
170 provisioning as co-benefit (Fig. 2b). In contrast, conserving the top-ranked 10% of land for  
171 biodiversity and water only can protect 21.7% of water and 43.6% of all species (Fig 2a), while  
172 maintaining 18% as carbon co-benefit (Fig. 2c). The implications of assigning different relative  
173 preferences to conserving NCPs magnify with increasing amounts of land dedicated to  
174 conservation. For example, with 10% and 30% of land managed for conservation the range of  
175 carbon conserved is 18% to 23.6% and 49.2% to 63.1% respectively, and the range in water  
176 conserved is 17.8% to 21.7% and 51.8% to 66.4% (Fig. 2a). Our results suggest that there is ample  
177 scope for identifying co-benefits from conserving these three assets, if explicit targets for each are  
178 considered, areas of importance for each asset are identified through multi-criteria optimization,  
179 and the range of relative weights given to each asset is comprehensively explored.



180  
181 **Fig. 2: Implications of different relative weights given to carbon or water over improving**  
182 **species conservation status.** (a) Each 'boomerang-shaped' segment of dots represents a series of  
183 conservation prioritisation scenarios with a common area budget (from 10% of land bottom left to  
184 100% at top-right). Axes indicate the proportion of all carbon and water provisioning assets  
185 conserved, colours represent the proportion of species for which conservation status could be  
186 improved in a given conservation scenario, and the point size indicates the difference in weighting  
187 given to carbon or water relative to biodiversity, ranking from none to equal weighting. (b-c)  
188 Global areas of importance if 10% (dark-brown), or 30% (yellow), of land area is managed for  
189 conservation while preferring (b) carbon protection over water or (c) water protection over carbon.  
190

191 The amount of land necessary to exclusively protect global biodiversity continues to be  
192 debated<sup>15,28,29</sup> In our analysis we found that, in the absence of any socio-economic constraints and  
193 ignoring other NCPs (here water and carbon), at least ~67% of land needs to be managed for

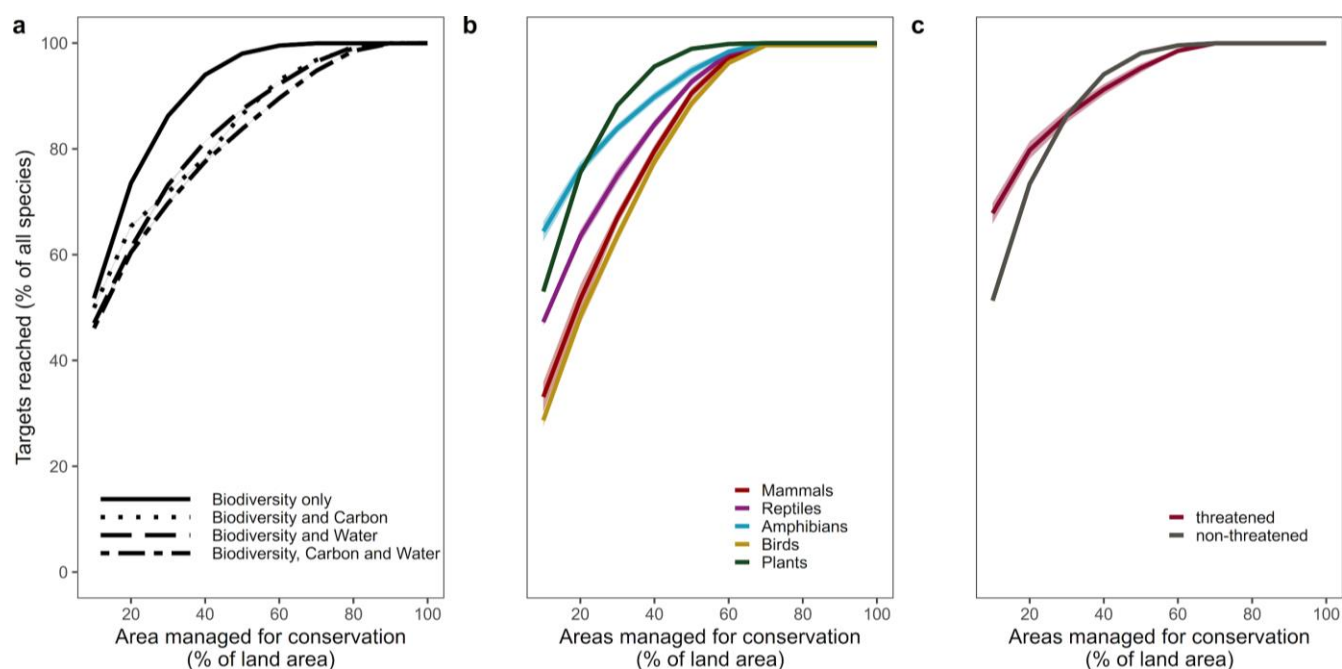
194 conservation globally, to improve the conservation status for terrestrial plants and vertebrates (Fig.  
195 3a). This is robust to the number of species included in the analyses, provided that they are a  
196 representative subset (see methods), with the variation typically being ~0.1% around the mean  
197 accumulation curves (Fig. 3a).

198 Optimally placing areas managed for conservation on 30% of the world's land is already  
199 sufficient to conserve 86.3% of all species considered in this analysis (ignoring existing protected  
200 areas, socio-economic constraints and other NCPs). Currently protected areas (PAs) are potentially  
201 sufficient to achieve persistence targets for 16.3% of the species analysed (SI Fig. 5, SI Fig. 6).  
202 However, by building on the current PA estate to increase areas managed for biodiversity  
203 conservation up to 30% of land, the conservation status of an additional 60.8% of the species could  
204 be improved (for a total of 77.1% of the species analysed). Therefore, there is an efficiency gap of  
205 only ~9.2% between re-designing global conservation efforts and optimally building on existing  
206 efforts.

207 When jointly optimizing target achievement for biodiversity, carbon and water (Fig. 3a),  
208 we found that selecting the top-ranked 30% (respectively 50%) of areas, a popular proposal for  
209 area-based conservation targets<sup>6</sup>, would conserve 62.4% (86.8%) of the estimated total carbon  
210 stock and 67.8% (90.7%) of all clean water provisioning, in addition to improving the conservation  
211 status for 69.7% (83.8%) of all species considered.

212 When optimizing conservation efforts for biodiversity only, we found that the groups that  
213 benefited the most were amphibian and plant species (Fig. 3b) and threatened species (Fig. 3c).  
214 The latter tend to have smaller range sizes and smaller absolute area targets than other groups and  
215 are inherently prioritized with area budgets  $\leq 30\%$  of land.

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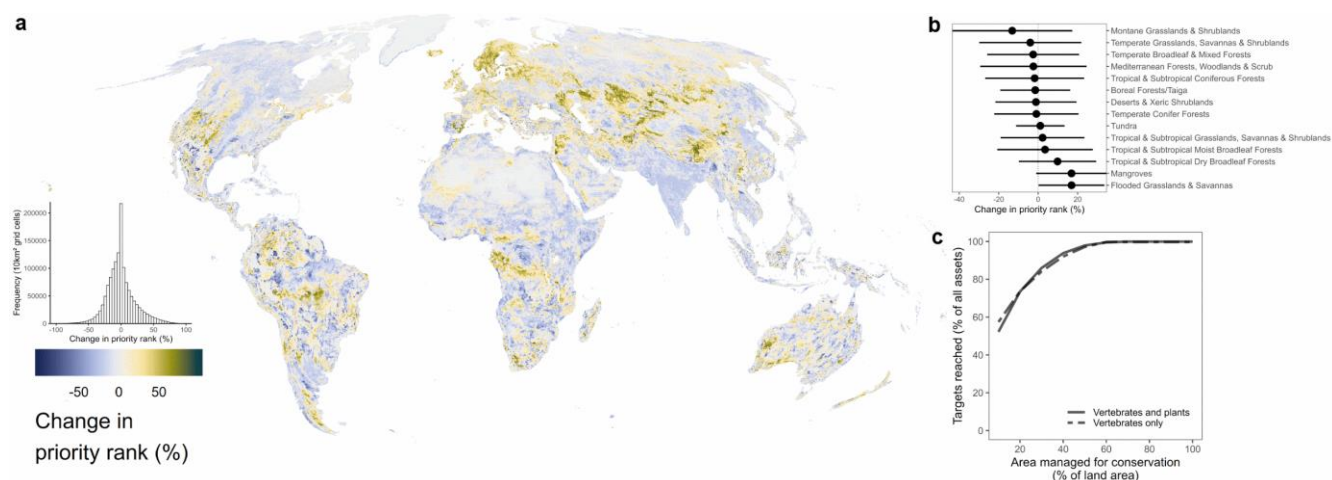
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218 **Fig. 3: Accumulation curves showing how the number of species targets met increases with**  
219 **amount of land optimally allocated to conservation.** Confidence bounds of accumulation curves  
220 indicate the uncertainty among representative sets and were generally found to be very small  
221 (~0.1%). This analysis ignores current protected areas and a version including those areas can be

222 found in the SI Fig. 6. (a) Target accumulation curves for analysis variants including other assets;  
223 (b) for different taxonomic groups when optimizing biodiversity only to conservation; (c) for  
224 species classified by IUCN as threatened or not (see Methods) when optimizing for biodiversity  
225 only.

226  
227 Our analysis included, for the first time in a global prioritisation analysis, a representative  
228 subset of plant distribution data totalling ~41% of described vascular plant species<sup>32</sup> (Fig. 4).  
229 Incorporating data on plants resulted in spatial shifts in areas of importance for conservation,  
230 particularly in the western United States of America, West-Central and South Africa, South-West  
231 Australia, Central Brazil, as well as northern Europe and central Asian steppes and mountains  
232 compared to an analysis where plants are ignored (Fig. 4a). Overall we found montane and  
233 temperate grasslands, Mediterranean savannas and shrublands biomes to increase in importance  
234 when considering plants, whereas flooded grasslands and mangroves lost relative importance (Fig.  
235 4b). The accumulation curves of species targets achieved were comparable between analysis  
236 variants with and without plants (Fig. 4c). Overall this indicates high surrogacy between vertebrate  
237 and plant species, despite spatial shifts in areas of importance (Fig. 4a).

238



239

240 **Fig. 4: Change in global areas of biodiversity importance after adding plant species.** (a)  
241 Calculated as the difference in areas of biodiversity importance with either plant species included  
242 or excluded. Positive changes (yellow to dark green) in rank imply an increase in priority if plant  
243 species are considered, while negative changes (light to dark blue) show a decrease in priority  
244 ranks. The map is at 10 km resolution in a Mollweide projection. (b) Average change in ranks per  
245 biome after plants have been added. (c) Representation curves of areas necessary to be managed  
246 for conservation with (solid) and without plants (dashed) included.

247

248 Areas of importance can vary spatially if species are given different weights, prioritising  
249 for instance the protection of threatened or more evolutionarily distinct species<sup>20,21</sup>. We tested the  
250 implication of prioritising the improvement of conservation status for these groups of species by  
251 weighting them by current conservation status or evolutionary distinctiveness. We found that doing  
252 so has only small inefficiency implications compared to a prioritisation without these weights  
253 (0.7% fewer biodiversity targets achieved when prioritising threatened species and 1.7% fewer

254 when prioritising evolutionarily distinct species with 10% of land). Yet, overall spatial patterns of  
255 the top-ranked 10% of areas of importance were comparable, with only minor differences, notably  
256 highlighting the importance of New Zealand and the Brazilian Amazon for conserving threatened  
257 species, the Mediterranean Basin, North-West USA, Florida and fringes of the Amazon Basin for  
258 conserving evolutionarily distinct species (SI Fig. 10). These results highlight that threatened or  
259 more evolutionary distinct species are well covered by other species<sup>30</sup>, and their full conservation  
260 can be achieved at minimal extra cost.

261

## 262 **Discussion**

263 How much area and where it should be managed for conservation is one of the key questions  
264 underpinning global biodiversity conventions and conservation planning discussions<sup>4,29</sup>. Our  
265 analyses suggest that even ambitious objectives such as ‘Half Earth’<sup>24</sup> or ‘30 by 30’<sup>6</sup> are  
266 insufficient to ensure that the conservation status of threatened species is improved and that non-  
267 threatened species remain so (Fig. 3). However, managing for conservation the top-ranked 30% of  
268 areas of importance for biodiversity, as identified here, can bring over 86% of the world's terrestrial  
269 vertebrate and a representative sample of plant species (of ~41% of all plant species) to a non-  
270 threatened conservation status, with further increases in area offering minor additional returns (Fig.  
271 3). Depending on the level of political ambition, an extra 20% of land could be dedicated to carbon  
272 storage as a contribution to climate regulation<sup>6</sup> and sustainable management of natural resources.  
273 However, our analysis shows that considerable co-benefits can already be achieved by managing  
274 an optimally placed 30% of land, if conservation of biodiversity, carbon and water is planned for  
275 with spatial optimization approaches (Fig. 2). We caution that these estimates, and equally those  
276 from previous studies<sup>6,14,16,23</sup>, can vary with different data and methods applied.

277 We ranked priority areas in order of importance for conservation management; but we note  
278 that specific forms of management are highly contextual and will depend on local anthropogenic  
279 pressures, governance and opportunity costs. Areas of biodiversity importance that require strict  
280 protection and active management, e.g. where narrow-ranging and threatened species occur might  
281 be suitable for protected area expansion<sup>31</sup>. Other effective area-based conservation measures<sup>32</sup>,  
282 such as watersheds managed primarily for water resource management or community-managed  
283 forests, might be more suitable in areas where biodiversity, carbon and water benefits are high but  
284 threats to species conservation remain low.

285 Our analyses does not impose any constraint on feasibility or equity among countries<sup>33</sup>,  
286 some of which contain over half of their territory in the top-ranked 10% of global importance for  
287 biodiversity, carbon and water provision (Fig. 1). Thus, there is a need for fair resourcing of the  
288 required management actions to offset the financial burden on some, predominantly tropical,  
289 countries<sup>33,34</sup>. Existing funding mechanisms should further explore opportunities to synergistically  
290 benefit both biodiversity and NCPs, as has been shown in the case of carbon<sup>26</sup>. Future, synergistic  
291 conservation prioritization efforts should particularly focus on incorporating socio-economic  
292 constraints<sup>35</sup>, consider integrated scenarios of the projected distribution of biodiversity, carbon and



293 water, support countries in identifying conservation actions at finer scale to maximize the  
294 achievement of national and global targets.

295 Our work also reveals research and data gaps in determining global areas of importance for  
296 terrestrial biodiversity conservation and NCPs. As NCPs we choose carbon and water because of  
297 their relevance to international conventions, but there are others we did not consider<sup>22</sup> such as food  
298 provisioning or cultural relevance. Similarly, many aspects of biodiversity remain under-  
299 represented - although we consider a significant portion of plant species on Earth, and we  
300 developed a framework to remove spatial bias in priority setting resulting from incomplete  
301 taxonomic coverage - there is a need to expand available data on other groups such as freshwater,  
302 soil and invertebrate species<sup>36,37</sup>. We also only investigated the influence of evolutionary history  
303 on vertebrate, but not plant species, for whom hotspots of evolutionary history might differ, and  
304 ignored other dimensions such as functional rarity<sup>38</sup>. Despite remaining gaps in taxonomic  
305 coverage and species checklists, our analysis also confirms the results of previous, broad-scale  
306 studies<sup>18,19,39</sup> that found high congruence between vertebrate and plant areas of importance, but we  
307 also highlight areas that would be overlooked if plants were not considered, especially so in dry  
308 grasslands, savannahs and Mediterranean shrublands (Fig. 4).

309 Our analyses highlight global areas of conservation importance that can maximize  
310 synergies across conventions (e.g. CBD, UNFCCC) and the SDGs. Particularly, our integrated  
311 maps could support governments in translating set targets (such as area-based conservation  
312 measures proposed for the 2021-2030 Strategic Plan of the CBD<sup>4</sup>) into national policies and  
313 actions on the ground and demonstrate how integrated spatial planning can be used to assist  
314 national biodiversity strategies. Meeting the SDGs requires real, transformative commitments that  
315 are yet to be enacted<sup>1</sup>, however, by maximizing synergies in efforts and resources, a pathway  
316 towards effective biodiversity conservation can be laid out for the next decade.

317

## 318 **Methods**

### 319 **Biodiversity data**

320 We utilized best available global species distribution data (overview in SI Table 1), including all  
321 extant terrestrial vertebrates and a representative proportion (41.31%) of all accepted plant species  
322 according to Plants of the World Online<sup>40</sup>. Extant mammal (5,685 species) and amphibian (6,660)  
323 distribution data were obtained from the International Union for Conservation of Nature Red List  
324 database (IUCN ver. 2019\_2<sup>41</sup>), while bird (10,953) range maps were obtained from Birdlife  
325 International<sup>42</sup>. Data on the distribution of reptiles were obtained from the IUCN database when  
326 available (6,830 species), otherwise from the Global Assessment of Reptile Distributions (GARD)  
327 database (3,755<sup>43</sup>). We obtained native plant range maps (193,954 species) from a variety of  
328 sources, including IUCN, Botanic Gardens Conservation International (BGCI) and the Botanical  
329 Information and Ecology Network (BIEN). The IUCN and BGCI data contains expert-based range  
330 maps and alpha-hulls (see Supporting Information), while the BIEN data consists mainly of  
331 herbarium collections, ecological plots and surveys<sup>44-52</sup>, that were used to construct conservative  
332 estimates of species ranges using species distribution models (SDMs). We benefited from version  
333 4.1 of BIEN, which includes data from RAINBIO<sup>53</sup>, TEAM<sup>54</sup>, The Royal Botanical Garden of

334 Sydney, Australia, and NeoTropTree<sup>55</sup>. Additional plant plot data from a number of networks and  
335 datasets have been included in BIEN and a full listing of the herbaria data used can be found in  
336 the extended acknowledgements and online ([http://bien.nceas.ucsb.edu/bien/data-](http://bien.nceas.ucsb.edu/bien/data-contributors/all/)  
337 [contributors/all/](http://bien.nceas.ucsb.edu/bien/data-contributors/all/)). In cases where multiple data sources were available for the same plant species,  
338 we preferentially used expert-based range maps to characterize a species' spatial distribution. A  
339 full description of the preparation and processing of the plant data can be found in the Supporting  
340 Information.

341 All vertebrate range maps were pre-processed following common practice<sup>56</sup> by selecting  
342 only those parts of a species' range where 1) it is extant or possibly extinct, 2) where it is native  
343 or reintroduced and 3) where the species is seasonally resident, breeding, non-breeding, migratory  
344 or where the seasonal occurrence is uncertain. We acknowledge that these ranges can contain some  
345 areas where the species is possibly extinct.

346

### 347 **Suitable habitat refinement**

348 Where data on species habitat and elevational preferences were available, we refined each species'  
349 range to obtain the area of habitat (AOH) in which the species could potentially persist<sup>57,58</sup>. Data  
350 on species habitat preferences and suitable elevational range were obtained from the IUCN Red  
351 List database<sup>41</sup> and, for an additional 1,452 reptile species in the GARD database, habitat  
352 preferences were compiled from an extensive literature search. For seasonally migrating birds and  
353 mammal species we ensured that separate habitat refinements were conducted for permanent and  
354 seasonally occupied areas of their range, that is, the breeding and non-breeding range. Whenever  
355 no habitat or elevation preferences were available for a given species, we used the full range except  
356 for areas considered to be artificial habitat type classes, such as arable or pasture land, plantations  
357 and built-up areas, noting that this could exclude areas suitable for some generalist species. For  
358 the AOH refinement we used a newly-developed global map (see Supporting Information) that  
359 follows the IUCN habitat classification system, thereby avoiding crosswalks between habitat  
360 preferences and land cover maps<sup>59</sup>. This data product integrates the best available land cover and  
361 climate data, while also using newly developed land-use data such as data on global forest  
362 management<sup>60</sup>. Finally, for each species and grid cell, we calculated the fractional amount (> 0-  
363 100%) of suitable habitat to include in the prioritisation analysis. Development of the habitat type  
364 map and all AOH refinement was performed on Google Earth Engine<sup>61</sup>.

365

### 366 **Global representativeness**

367 There is considerable bias and variability in the completeness of biodiversity records globally,  
368 particularly so for plant species<sup>62</sup>. To estimate the amount of geographic bias in completeness of  
369 distribution data among plants, we first estimated the proportion of species for which we had  
370 distribution data relative to the number of species known to occur in the regional checklists of  
371 World Checklist of Vascular Plants database<sup>40</sup>, which provides for each accepted species name its  
372 native regions from the World Geographical Scheme for Recording Plant Distributions  
373 (WGSRPD,<sup>64</sup>). We used geographic delineations for 50 WGSRPD level 2 regions<sup>64</sup>, but excluded  
374 Antarctica and mid-Atlantic islands (Saint Helena and Ascension) for which we had no plant

375 records. The proportion of species for which we had range data varied from 11% in islands of the  
376 North Pacific up to 100% in the Russian far east (mean 60.1%  $\pm$  24.5 SD). However, for 48 of the  
377 50 WCSRPD regions we had distribution data for over >10% of all described plants known to occur  
378 natively in that region, (the exception being islands in the South-West and South-Central Pacific).  
379 For 44 of these 50 regions we had distribution data for >40% of described plants in those regions.

380 Having identified 10% as the minimum common denominator of completeness across most  
381 regions, we then used an iterative heuristic algorithm, to construct ‘representative’ subsets  
382 consisting of random samples that approximated 10% of species from each WGSRPD level 2  
383 region while accounting for the fact that some species occur across multiple regions. To test if this  
384 approach yielded sets representative of biogeographic patterns of the full dataset, we compared the  
385 spatial patterns of scaled vertebrate species richness to the 10% sets of these species for each  
386 WGSRPD level 2 regions, random subsets of 10% of all vertebrates and for all vertebrates  
387 combined. We performed the test on vertebrates because we had range maps for ~95% of terrestrial  
388 vertebrates described, therefore we can assess if our subsampling to representative sets can  
389 replicate “true” patterns in species richness obtained with a complete sample of species in a  
390 taxonomic group. Spatial patterns of scaled species richness were identical across those sets,  
391 suggesting that this sampling approach can account for incomplete coverage (SI Fig 7a).

392 We also checked if the frequency distribution of range sizes within our subsets matched  
393 the range size distribution of the entire set using mammals as a test group, and found very modest  
394 differences between the full set and multiple subsets (SI Fig 7b). Having confirmed that this  
395 procedure recreates correct patterns of conservation priorities and it does not alter the range-size  
396 distribution (SI Fig 7), we proceeded to create 10 subsets of ~10% of plant species known to occur  
397 in each WGSRPD level 2 region and ten non-overlapping subsets of 10% of vertebrate species for  
398 all of our analyses. We found little difference among representation curves regardless of whether  
399 multiple representative subsets or all species were included in the SCP, although there was greater  
400 efficiency in the latter (SI Fig. 8).

401

## 402 **Carbon data**

403 We used spatial estimates of the density of aboveground and belowground biomass carbon and  
404 vulnerable soil carbon<sup>9</sup>. Estimates for aboveground carbon (AGC) were created by selecting the  
405 best available carbon maps for different types of vegetation classes, identified spatially using the  
406 Copernicus Land Cover map in 2015<sup>65</sup>. We used Santoro *et al.* as a baseline for a global carbon  
407 biomass map<sup>66,67</sup>, which has been shown to be the most accurate, especially so for ‘tree’ covered  
408 land. In addition, we used more detailed estimates of above-ground biomass for African “open  
409 forest” and “shrubland” land cover<sup>68</sup>, global “herbaceous vegetation” and “moss and lichen” land  
410 cover<sup>69</sup> and “cropland” and “bare/sparse vegetation” land-cover classes<sup>70</sup>. To map below-ground  
411 carbon, we applied corrected root-to-shoot ratios<sup>71</sup> obtained from the Intergovernmental Panel on  
412 Climate Change (IPCC) technical guidance documents<sup>72</sup>. A newly developed forest management  
413 layer<sup>60</sup> was used to update biomass density, by averaging estimates from 2010 and 2017<sup>66</sup> in the  
414 most dynamic tree-covered classes (e.g. short rotation plantations, agroforestry).

415 The map of vulnerable soil organic carbon was created following IPCC Guidelines for  
416 National Greenhouse Inventories to estimate emissions and removals associated with changes in  
417 land use<sup>72</sup>. Vulnerable soil organic carbon was defined as those carbon stocks that could potentially  
418 be lost during the coming 30 years as a result of land use. We used recently published data on  
419 baseline soil organic carbon stocks<sup>73</sup>, and vulnerable stocks were estimated separately for mineral  
420 and organic soils. Organic soils were defined as those soils with  $\geq 5\%$  probability of being a  
421 Histosols according to USDA soil orders taxonomy<sup>74</sup>. All other soils were considered to be mineral  
422 soils. A 30cm depth was used to estimate vulnerable carbon stocks on mineral soils, while 200cm  
423 depth was used for organic soils. IPCC change factors (mineral soils) and emission factors (for  
424 organic soils) were used to estimate vulnerable soil organic carbon stocks according to IPCC land  
425 cover categories and climate zones. To be consistent with biomass carbon estimations, we created  
426 a crosswalk between the Copernicus global land cover map<sup>65</sup> and IPCC land cover classes. The  
427 newly developed forest management layer<sup>60</sup> was used to refine vulnerable carbon stock estimates  
428 for mineral soils, whilst managed forest with organic soils were excluded from this assessment  
429 given that due to drainage, these areas would be more suitable for restoration than for conservation  
430 action. Finally, all global carbon estimates were reprojected, summed and aggregated (arithmetic  
431 mean) to 10 km to match the biodiversity data in scale.

432

### 433 **Water data**

434 For capturing water provisioning, we used estimates of potential clean water provision calculated  
435 by WaterWorld<sup>75</sup> and Co\$ting Nature<sup>76</sup>. This quantity calculates for each grid cell the volume of  
436 water available, as the accumulated water balance from upstream based on rainfall, fog and  
437 snowmelt sources minus actual evapotranspiration. Second, clean water was assessed using the  
438 Human Footprint on Water Quality (HFWQ) index, which is a measure of the extent to which  
439 water runoff is drawn from contaminating human land uses: both point (urban, roads, mining, oil  
440 and gas) and nonpoint (unprotected cropland, unprotected pasture) sources. The HFWQ index is  
441 calculated by cumulating the downstream runoff from polluting and non-polluting land uses and  
442 expressing the former runoff as a proportion of the total runoff. This is calculated by assigning an  
443 associated percentage (or dilution) intensity fraction to each land-use class (default values taken  
444 from<sup>76</sup>). The potential clean water provisioning service is calculated for each cell as the inverse of  
445 clean water (i.e. 100 - HFWQ) available from upstream. For the analysis we ranked each grid per  
446 river basin<sup>77</sup> to determine their relative importance in delivering clean water within the basin.

447

### 448 **Prioritisation analysis**

449 We determined global areas of importance to be managed for conserving biodiversity, carbon and  
450 water by using a spatial conservation prioritisation approach (SCP<sup>78</sup>). We divided the world in 10  
451 km resolution 'planning units' (PUs, the cells of the land-surface area grids), in which 'features'  
452 are distributed (each species, plus carbon stocks and water provision), for which we establish  
453 conservation targets<sup>79</sup>. Each PU had an area 'cost' subject to 'budget' constraints (the total amount  
454 of the terrestrial land-surface within a PU). For biodiversity, we defined species-specific targets

455 aimed at conserving the area of habitat (AOH) for a species to improve in conservation status (<sup>15</sup>,  
456 see Supporting Information) and for each species we calculated the amount of suitable habitat  
457 within each PU. For tonnes of carbon storage ( $\frac{tC}{km^2}$ ) and/or volume of water ( $\frac{Mm^3}{km^2}$ ), we maximized  
458 the total amount present in each PU. All PUs had a cost equivalent to the amount of land within  
459 them ( $\{0 < c \leq 1\}$ ), which we calculated from Copernicus land-cover data<sup>65</sup>. As global budget  
460 (B) we set different percentages of the terrestrial land surface area starting at 10%, then increasing  
461 by 10% increments up until all targets were met.

#### 462 Problem formulation

463 Areas of importance for the conservation of biodiversity, carbon and water were determined by  
464 solving a global optimization problem. For each feature  $j$  included in the analysis we aimed to  
465 minimize the proportional shortfall<sup>80</sup> in achieving each representation target  $t_j$  given a planning  
466 unit cost  $c$  and an area budget  $B$  (10, 20, ..., 100% of  $\sum_{i=1}^I c_i$  the planet). For all species,  $t$  is the  
467 target shortfall, that is, the difference between the part of an AOH that is included in the solution,  
468 and the amount that is necessary to be conserved for the species to improve in conservation status  
469 (<sup>15</sup>, Supporting Information), while for carbon storage and water provisioning  $t$  is the total amount  
470 available on the terrestrial land (the target is 100%). The problem is formulated as follows:

471 *Minimize*  $\sum_{j=1}^J w_j \frac{y_j}{t_j}$

472 *Subject to*

473 
$$\sum_{i=1}^I x_i r_{ij} + y_j \geq t_j \forall j \in J$$

474 
$$\sum_{i=1}^I x_i c_i \leq B, \text{ where } 0 \leq x_i \leq 1 \forall i \in I$$

475  
476 where  $r_{i,j}$  is the amount (suitable habitat in  $km^2$ , total tons of carbon  $\frac{tC}{km^2}$  or volume of water  $\frac{Mm^3}{km^2}$ )  
477 of feature  $j$  in planning unit  $i$ ,  $y_j$  is the shortfall for feature  $j$ ,  $t_j$  is the target for feature  $j$ ,  $c_i$  is the  
478 cost of grid cell  $i$  (the fractional area within the planning unit),  $B$  is the budget of the problem,  $x_i$   
479 is a proportional decision variable [0-1], where 1 means that the full PU and values  $\geq 0$  a fraction  
480 of the PU is selected, and  $W_j$  is the weight assigned to feature  $j$ . We tested different  $W_j$  of carbon,  
481 respectively water, relative to biodiversity and different weights among species based on their  
482 global threat status and/or evolutionary distinctiveness (Supporting Information). The problem is  
483 then solved for each budget incrementally, by ‘locking in’ previous solutions with lower area-  
484 budget prior to running the next prioritisation, effectively building nested sets of priorities with  
485 increasing budget  $B$ .

#### 486 Analysis variants

487 For a separate analysis, we constrained the optimization by locking in the fraction of currently  
488 protected areas and adjusted the starting budget accordingly (Supporting Information). We then

489 jointly optimized globally for biodiversity, carbon and water by minimizing the proportional  
490 shortfall<sup>80</sup> in reaching the targets for each given area budget  $B$  (10, 20, ..., 100% of the planet).

491 We furthermore considered a number of optimization variants in which we modified either  
492 the targets or weights assigned to each feature (biodiversity, carbon and/or water). For biodiversity,  
493 we also considered variants distinguishing between species intraspecific variation, threat status  
494 and evolutionary distinctiveness (SI Table 2). To capture intraspecific variation, we considered  
495 each part of a species range occurring in geographically separate biomes as a separate feature with  
496 its own target<sup>28</sup>, e.g. the Tiger (*Panthera tigris*) was split into five separate features, one for each  
497 of the five biomes overlapping the tiger range (Supporting Information). However, we only  
498 considered a split for features in which at least 2,200 km<sup>2</sup> of AOH (the minimum absolute target  
499 area) was contained within a different biome compared to the biome with the majority of the  
500 species range. Compared to a version without these splits and when optimizing for biodiversity,  
501 carbon and water, overall differences were relatively minor (SI Fig. 11), but potentially locally  
502 important. We also collated data on species current threat status and, for vertebrates, data on their  
503 evolutionary distinctiveness (Supporting Information), and then calculated weights for each  
504 species following<sup>13</sup>. We then optimized all variants by minimizing the target-weighted shortfalls  
505 across all biodiversity features, subject to budget constraints.

506 We set weights for carbon storage and water provisioning relative to biodiversity in all  
507 analyses variants that included these assets. To do so we assigned sequences of weights from  
508 ‘none’ up to ‘equal’ importance by weighting carbon and water as follows:  $w_k = 1 + \sum_{j=1}^J w_j$ ,  
509  $w_k$  is the weight for carbon and water,  $J$  is the total number of species in the analysis, and  $\sum_{j=1}^J w_j$   
510 is the cumulative sum of all species weights. This weighting ensures that carbon is given equal  
511 importance to all species combined and that feature targets are treated equally in the optimization.  
512 We also created separate scenarios where  $w_k$  is set to  $\frac{1}{10}, \frac{2}{10}, \dots$  of the equal weighting relative to  
513 the cumulative shortfall for biodiversity. We visualized all scenarios with increasing budget and  
514 by the shortfall in carbon, water and improvement in species conservation status (Fig. 2) Because  
515 of the high computational cost of calculating  $(2N_w - 1) * N_B$  prioritizations, where  $N_w$  is the  
516 number of weights and  $N_B$  the number of budgets, for each of the 10 representative sets, we  
517 assessed differing weights at 50 km rather than 10 km resolution. However, we note that compared  
518 to a 10 km resolution, both spatial patterns and accumulation curves were highly similar (See  
519 Supporting Information and SI Fig. 9) and we don’t expect results to differ because of differences  
520 in resolution.

## 521 **Optimization algorithm and ranking**

522 All SCP variants were solved using an integer linear programming (ILP) approach. Compared to  
523 other conservation planning solutions that rely on simulated annealing or heuristics<sup>81</sup>, ILP has been  
524 shown to outcompete those approaches in both speed and solution performance, being able to  
525 reliably find optimal solutions<sup>82,83</sup>. We ran all problem variants under each budgetary constraints  
526 (10%, 20%...100% of land), each with a representative set of species and solved them to optimality  
527 using proportional decisions (e.g. asking which fraction of a grid cell is part of the solution). For  
528 each problem variant, we therefore obtained 10 nested sets of priorities (priority ranks), each

529 resulting from solving all budgetary constraints with a representative set of species. We  
530 summarized these priority ranks through an arithmetic mean while also separately calculating the  
531 coefficient of variation as a measure of uncertainty in priorities across representative subsets (SI  
532 Fig. 1). Selected planning units in the obtained solutions were investigated for the representation  
533 of input features by taxonomic group, threatened species and biomes.

534 All data preparation and analysis was conducted in R<sup>84</sup> mainly relying on the ‘prioritizr’  
535 package<sup>85</sup> with the Gurobi solver enabled (ver 8.11,<sup>86</sup>).

537 **Data availability** All produced integrated maps will be made available through  
538 <https://unbiodiversitylab.org/> and a data repository upon acceptance. The raw input data can be  
539 requested from the respective data providers, namely IUCN, GARD, Birdlife International, Kew  
540 Gardens and predicted plant distribution data will be made available as part of the BIEN  
541 initiative<sup>44</sup>. The IUCN habitat type map used to construct the AOH is made available in the  
542 Supporting Information. Any additional data not listed can be made available from the authors  
543 upon reasonable request or will be openly published separately.

544 **Code availability** Code to reproduce the main results will be made available upon acceptance.

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563  
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## Supporting online material

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### 758 **Material and Methods**

#### 759 **Choice of resolution**

760 We chose a spatial resolution of 10km to adequately capture global biodiversity and nature's  
761 contribution to people per grid cell. For the biodiversity data we used estimates of a species global  
762 range. Previous studies have recommended coarser spatial resolution (~110km) when using  
763 species range maps as such, to better match equally downscaled atlas data considered to be the  
764 'true' distribution of a species<sup>1</sup>, however, this can result in more costly prioritisations due to  
765 commission errors, without meaningful reductions in spatial biases<sup>2</sup>. In this study we refined a  
766 species range to an Area of Habitat (AOH,<sup>3</sup>) to minimize commission errors (false presences). This  
767 was done at a spatial resolution similar or even coarser than in comparable studies relying on the  
768 same range data<sup>4-7</sup>. Lastly, we also created separate maps of all analyses at 50km resolution to  
769 investigate differences on identified areas of biodiversity importance (SI Fig. 9), and found overall  
770 little to no difference between analyses done at these different resolutions. Nevertheless, we  
771 caution that the identified global areas of importance should not be used to inform conservation  
772 decisions on local or landscape scales.

773

#### 774 **Plant data preparation**

775 To this date, there does not exist a single and consistent data source for species range data of all  
776 described plant species globally<sup>8-10</sup>. The total number of plant species globally is still unknown,  
777 with existing estimates ranging between 352,282 species<sup>11</sup> and over 434,934 species<sup>9</sup>. To obtain a  
778 representative subset of described plant species, the NatureMap consortium gathered the best  
779 available plant distribution data from a variety of sources and types, acknowledging that none of  
780 them are without errors and biases, which we addressed by calculating spatially representative sets,  
781 each approximating the same proportion of species known to exist in an area, across the planet.

782 We first relied on expert-based global range estimates created by the International Union  
783 for Conservation of Nature (IUCN), Royal Botanic Gardens, Kew, and Botanic Gardens  
784 Conservation International (BGCI). For many plant species only curated point estimates of their  
785 range were available. Based on this data, range estimates were constructed using alpha-hulls, a  
786 generalization of convex hulls that are particularly useful for estimating species ranges whose  
787 habitat is irregularly shaped<sup>12</sup> or where populations are spatially structured<sup>13</sup>. Parameters for alpha-  
788 hulls creation were adaptively selected, starting with initial alpha values - a parameter constraining  
789 the hull triangulation - of 2 or 3 recommended by the IUCN Red List categories and criteria, but  
790 adjusted for the distribution of records so that at least 95% of the records were included within the  
791 estimated range. The value of alpha ranges from zero (i.e. the finest resolution defined by the given  
792 set of points) to infinity (i.e. the coarsest resolution defined by the convex-hull). Since variations  
793 in alpha can also affect subpopulation structure (i.e. number of subpopulations), we combined  
794 alpha-hulls with the "1/10<sup>th</sup> max" circular buffer method (i.e. the buffer size is set to the tenth of  
795 the maximum interpoint distance) to better capture subpopulation structure<sup>13</sup>. Finally, we limited  
796 the number of subpopulations to maximum of 10 and if the conditions above are not met (i.e. >=



797 95% of records inside the estimated range and  $\leq 10$  subpopulations), a minimum convex hull or  
798 a buffer built with the “1/10<sup>th</sup> max” method is drawn around each record<sup>13</sup>. We split the occurrence  
799 records geographically into separate parts in cases the alpha hulls could not be constructed (for  
800 instance close to 180° longitude). In these cases, we applied the alpha-hull method to each  
801 individual dataset and merged the calculated hulls back into one unique range. All alpha hulls and  
802 “1/10<sup>th</sup> max” buffers were created using the *rangeBuilder* package<sup>14</sup>. In total, data for 8,702 plant  
803 species ranges could be obtained through both sources, including 4,598 tree species from BGCI  
804 and 4,104 plant species from IUCN.

805 For plant species not yet assessed by IUCN or BGCI, we relied on modelled range estimates  
806 derived from occurrence records acquired through the Botanical Information and Ecology Network  
807 (BIEN) initiative, the Global Biodiversity Information Facility (GBIF.org 2019,  
808 <https://doi.org/10.15468/dl.gvt20i>) and from iNaturalist ([www.inaturalist.org](http://www.inaturalist.org)). Not all research  
809 grade observations from iNaturalist are transferred to GBIF and we thus downloaded all research  
810 grade iNaturalist plant data separately and merged them with the GBIF data, while removing  
811 duplicate observations.

812 The observations in the BIEN database are the product of contributions by 1,076 different  
813 data contributors, including numerous individual herbaria, and data indexers of herbaria (550+ are  
814 listed in Index Herbariorum), that were used to construct conservative estimates of species ranges  
815 using species distribution models (SDMs). For details of specimen data sources see<sup>9,16</sup>. We  
816 benefited from version 4.1 of BIEN, which includes data from RAINBIO<sup>17</sup>, TEAM<sup>18</sup>, The Royal  
817 Botanical Garden of Sydney, Australia, and NeoTropTree<sup>19</sup>. Additional plant plot data from a  
818 number of networks and datasets have been included in BIEN<sup>8,9,16,20–25</sup> and a full listing of the  
819 herbaria data used can be found in the extended acknowledgements below and online  
820 (<http://bien.nceas.ucsb.edu/bien/data-contributors/all/>).

821 Taxon names associated with BIEN occurrence records were first corrected for  
822 misspellings, homonyms (e.g. plant and animal species with identical names) and synonyms.  
823 Afterwards all taxon names were standardized using TNRS v4.0 at default settings with checklists  
824 from Tropicos, The Plant List, USDA Plants, Global Compositae Checklist, ILDIS<sup>26</sup>. Standard  
825 BIEN preprocessing procedures furthermore ensure that species outside their native ranges were  
826 removed using lists of endemic taxa and the Native Species Resolver (NSR;  
827 <https://github.com/ojalaquellueva/nsr>). Observations were furthermore flagged and removed as  
828 cultivated based on keywords in the original observation metadata.

829 We applied the following preprocessing steps to all plant occurrence records from BIEN,  
830 GBIF and iNaturalist. We removed all occurrence records that (1) had no or impossible coordinates  
831 (e.g.  $< 90^\circ$  S latitude or longitude  $> 180^\circ$  or  $< -180^\circ$ ), (2) had a coordinate uncertainty greater than  
832 10 km, (3) had identical latitude or longitude coordinates, duplicate records or where coordinates  
833 had a precision smaller than one digit, (4) removed occurrence records in the vicinity (10 km  
834 distance) of country capitals or outside the lowest declared political division in the case of BIEN  
835 using the Geographic Name Resolution Service (GNRS;  
836 <http://bien.nceas.ucsb.edu/bien/tools/gnrs/>), near country or province centroids (1 km), or in the  
837 vicinity (1 km) of known zoos, botanical gardens or herbaria and (5) removed all occurrence points  
838 that fell into the open ocean<sup>27</sup>. For the modelling, we merged plant occurrence records from GBIF  
839 and iNaturalist into one dataset per species and only included those records from BIEN that were  
840 not already present in other data sources.

841 Plant species can have varying uncertainties in taxonomies and geographic spread and quite  
842 commonly occur in regions where the species is not considered native. In this study we relied on  
843 taxonomic and geographic information from the Plants of the World online (POWO) database,  
844 which provides for each accepted species name its native World Geographical Scheme for  
845 Recording Plant Distributions (WGSRPD) regions<sup>28,29</sup>. We only included plant species in the

846 analysis whose name could be matched to POWO taxonomy (either as accepted name or as  
847 synonym) and which had at least one occupied grid cell in all WGSRPD level 2 regions in which  
848 the species is known to be native, to reduce influences of sampling biases. Lastly, we post-hoc  
849 removed from each predicted distribution all unconnected isolated patches outside native  
850 WGSRPD regions, which we identified through connected component labeling<sup>30</sup>.

851 For modelling plant species distributions we used a number of environmental covariates,  
852 which are adequate for the spatial scale (global at 10 km) of our modelling approach<sup>31</sup>. Data on  
853 present (1979-2013) climatic conditions (Annual Mean Temperature, Mean Diurnal Range,  
854 Annual precipitation, Precipitation seasonality, Precipitation of Warmest Quarter, Precipitation of  
855 Coldest Quarter, maximum accumulated Aridity (consecutive water deficit during months where  
856 potential evapotranspiration exceed precipitation) & estimated relative Precipitation of Warmest

857 Quarter = 
$$\frac{\text{Precipitation of Warmest Quarter}}{(\text{Precipitation of Warmest Quarter} + \text{Precipitation of Coldest Quarter})}$$

858 were obtained from CHELSA (<http://chelsa-climate.org/>,<sup>32</sup>). Data on global aridity<sup>33</sup> and  
859 soil conditions (bulk density, % clay content, depth to bedrock, pH & % silt content all averaged  
860 over full depth to 200cm) from <https://soilgrids.org><sup>34</sup>. These covariates were chosen based on  
861 their ecological relevance for plant species and on having global correlations < 0.7 with each  
862 other<sup>35</sup>. All environmental covariates were aggregated (arithmetic mean) to 10 km globally and  
863 projected to an equal-area Mollweide projection.

864

## 865 **Point process modelling**

866

867 For all plant species with 10 or more records available we fitted Poisson point process models  
868 (closely related to Maxent) using regularized down weighted Poisson regression models<sup>36</sup>, fitted  
869 with the R package glmnet<sup>37</sup>. We used up to a maximum of 20,000 background points in total,  
870 adjusted based on the total number of grid cells within the domain, and chose a spatial domain for  
871 predictions based on the biomes a species occurred in<sup>38</sup>. All candidate predictors were further  
872 filtered for collinearity for each individual species separately<sup>35</sup>, with highly collinear covariates  
873 (Pearson'  $r > 0.7$ ) within the domain removed.

874 Five independent folds were trained for cross validation, where folds were assigned based  
875 on spatial clusters to remove the influence of spatial autocorrelation on cross-validated  
876 performance statistics. Linear (all species), quadratic (species with >100 records), and product  
877 (species with >200 records) features were used. Regularization parameters for each model were  
878 determined based on one standard deviation below the minimum variance<sup>37</sup>. This resulted in five  
879 models per species which were then combined in an unweighted ensemble by calculating the  
880 arithmetic mean and standard deviation of the folds. Finally, the continuous predictions were  
881 thresholded to obtain binary presence/absence predictions based on the 5th percentile of the  
882 ensemble predictions.

883

## 884 **Range-bagging models**

885 For all plant species with between five and lower than ten records we utilized a 'range bagging'  
886 approach, which is a stochastic, hull-based method that can estimate climate niches from an  
887 ensemble of underfit models<sup>39,40</sup>, and is therefore well suited for smaller datasets. We randomly  
888 sampled 100 times a proportion  $p$  of records ( $p = 0.33$ , based on recommendations in<sup>39</sup>) and a  
889 subset  $d$  of environmental variables ( $d = 2$ ,<sup>39</sup>). A convex hull is then projected around the  
890 subsampled records in environmental space, with a record considered part of the species range if  
891 its environmental conditions fall within the hull. We then chose a voting threshold of 0.165  
892 ( $=0.33/2$ ), implying that the grid cell is part of the species range at least half the time for each  
893 subsample. Upon visual inspection we generally found that this threshold leads to relatively

894 conservative predictions. All range bagging records and environmental predictors were subjected  
895 to the same selection rules as for the point process models discussed above.

896

### 897 **Grid cell data**

898 For plant species with less than three covered grid cells records we used only those grid cells the  
899 points fall, which often describe the full distribution of the species known to science, many of  
900 which are globally rare<sup>9</sup>.

### 901 **Ancillary data**

902 To account for current areas managed for conservation, we included data on current global  
903 protected areas from the global World Database on Protected Areas (WDPA, April 2019 version,  
904 IUCN and UNEP-WCMC 2019). Following commonly used WDPA preparation standards<sup>41</sup>, we  
905 excluded protected areas whose status was ‘proposed’ or ‘not reported’ and furthermore removed  
906 UNESCO Man & Biosphere reserves. This figure, however, does not include data from countries  
907 that have restricted the sharing of their dataset through the WDPA, such as China, Estonia, Saint  
908 Helena, Ascension and Tristan da Cunha<sup>41</sup>. All layers were first rasterized at 1 km, then aggregated  
909 to 10 km by calculating the relative fraction of area protected, so that small PAs were not lost. As  
910 a result, ~15% of the land surface was identified as being protected in the prioritisation analysis.  
911 Lastly, we prepared data on terrestrial biomes and ecoregions  
912 (<http://ecoregions2017.appspot.com>,<sup>38</sup>), which were likewise rasterized to 10 km resolution using  
913 a modal aggregation.

914

### 915 **Habitat types map**

916

917 Not all parts of a species range are equally suitable to allow a species to persist, thus requiring a  
918 refinement to an area of suitable habitat (AOH,<sup>3,5</sup>). In the past this refinement has commonly been  
919 attempted using a crosswalk<sup>42</sup> between land-cover legends and habitat type information from the  
920 IUCN habitat type classification<sup>43</sup>. Crosswalks between different thematic legends can potentially  
921 cause issues such as inseparability of habitat types that are identical in land cover but different in  
922 climatic and soil conditions (e.g. tropical moist lowland forest and tropical mangrove forest). We  
923 developed a new global habitat type layer that follows the IUCN habitat classification system<sup>43</sup>.  
924 This layer is an intersection of the best currently available land cover dataset<sup>44</sup>, data on climate<sup>45</sup>  
925 and other ancillary datasets, such as a novel data product on the distribution of global  
926 anthropogenically modified forests including tropical and temperate plantations (Lesiv et al.  
927 unpublished). Using this layer we refined all species ranges (see methods) at 1 km globally and  
928 calculated the fraction of suitable habitat per 10 km grid cell. We make a version of this global  
929 layer available as part of this manuscript<sup>46</sup>.

930

### 931 **Prioritisation analysis**

#### 932 **Target setting**

933 One of the most impactful decisions in spatial conservation planning frameworks is the definition  
934 of feature targets. In the past, many studies set targets for species representation according to  
935 rules<sup>47-49</sup> or area-based policies (e.g. 30% of a species range), which run the risk of leading to an  
936 excess of area for wide-ranging species and arbitrariness. We set targets relative to the amount of  
937 habitat necessary to improve a species conservation status as inspired by IUCN criteria<sup>50</sup>. We  
938 recognise that this only takes the range (area of suitable habitat) into account, and ignores other

939 factors of extinction risk, such as population size and trends, but the purpose is to provide  
940 ecologically credible area-based conservation targets, rather than estimating extinction risk. For  
941 all species, these targets were defined as

$$942 \quad t_i = \frac{\min(\max(2200 \text{ km}^2, 0.8 * A_{AOH_i}), 1e^6 \text{ km}^2)}{A_{AOH_i}},$$

943 where  $t_i$  is the relative target for a given species  $i$  and  $A_{AOH_i}$  the total area of suitable habitat for  
944 the species<sup>50</sup>. Whenever the numerator exceeded the  $A_{AOH_i}$  (e.g. is smaller than 2200 km<sup>2</sup>), the  
945 target was set to the whole AOH (100%), following<sup>37</sup>. In the prioritisation analysis we ranked each  
946 PU after formulating and solving a budget limited formulation of the reserve selection problem  
947 that aims to maximize conservation benefits.

## 948 **Species-specific weights**

949 Areas of biodiversity importance can vary depending on whether greater weight is placed on  
950 evolutionarily distinct<sup>51</sup> and/or threatened species<sup>52</sup>. For this analysis we obtained data on the  
951 evolutionary distinctiveness (ED) scores for amphibians (99.7% of all species considered), birds  
952 (100%), mammals (100%) and reptiles (71.9%) from the EDGE program (EDGE 2019 list,<sup>53</sup>). For  
953 plant species there does not yet exist a species-resolved phylogeny<sup>54</sup> and further research is  
954 necessary to fill that gap. Whenever ED scores could not be matched to species names, we used  
955 the congeneric or family-wide ED average<sup>55</sup>. ED scores represent the amount of unique  
956 evolutionary history of a species<sup>56,57</sup>, thus placing greater weight on evolutionary older and most  
957 distinctive lineages in a phylogeny. For example, Cuba and Hispaniola have evolutionary  
958 significance because these were the only two species of *Solenodon* that exist; the only members of  
959 the mammal family *Solenodontidae* which diverged from all other mammals over 60 million years  
960 ago, thus representing a disproportionate amount of evolutionary history. Data on the threat  
961 category (TC) of species was obtained from IUCN and encoded as numerical weight. In addition,  
962 for plant species we used data from the ThreatSearch online database<sup>58</sup>. We followed Pouzols et  
963 al. (2014) and assigned a weight of 8 to Critically Endangered species (CR), 6 to Endangered (EN),  
964 4 to Vulnerable (VU), 2 to Near Threatened (NT) and 1 to species of Least Concern (1). Plant  
965 species without a standardized IUCN threat category, but which are considered threatened  
966 according to BGCI, were assigned a weight of 6. Species without sufficient current TC information  
967 or that were Data Deficient (DD) were assigned a conservative score of 2, given that many Data  
968 Deficient species are likely threatened with extinction<sup>59,60</sup>, especially so for plant species<sup>11</sup>. We  
969 separately incorporated for each species either the evolutionary distinctiveness (ED) score or the  
970 threat category (TC) as weight in the prioritisation, using weight from TC weights<sup>52</sup>. In total, we  
971 included data on ED weights for 34,308 species, TC weights for 43,211 species and calculated  
972 separated problem variants where data for both (29,780 species) is available (SI Fig. 10).

973

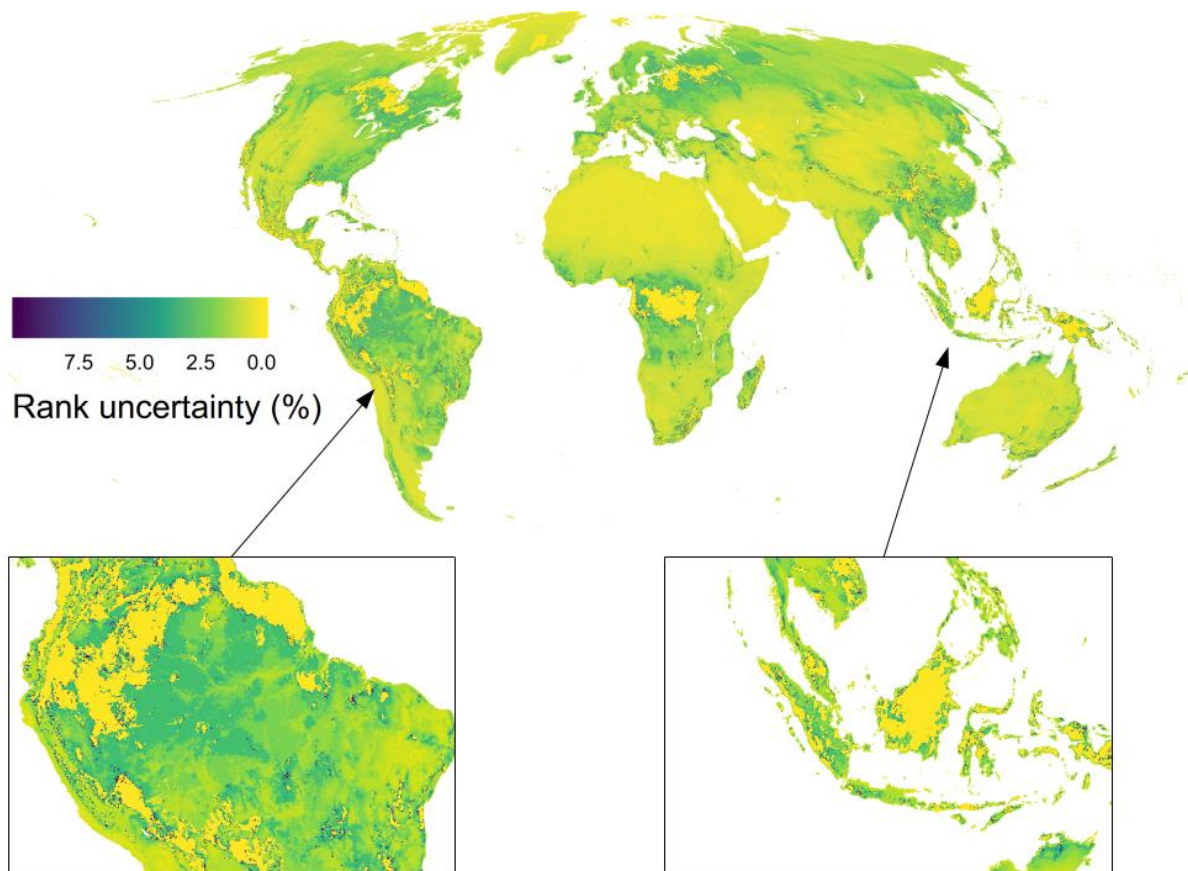
## 974 **Supplementary figures and tables**

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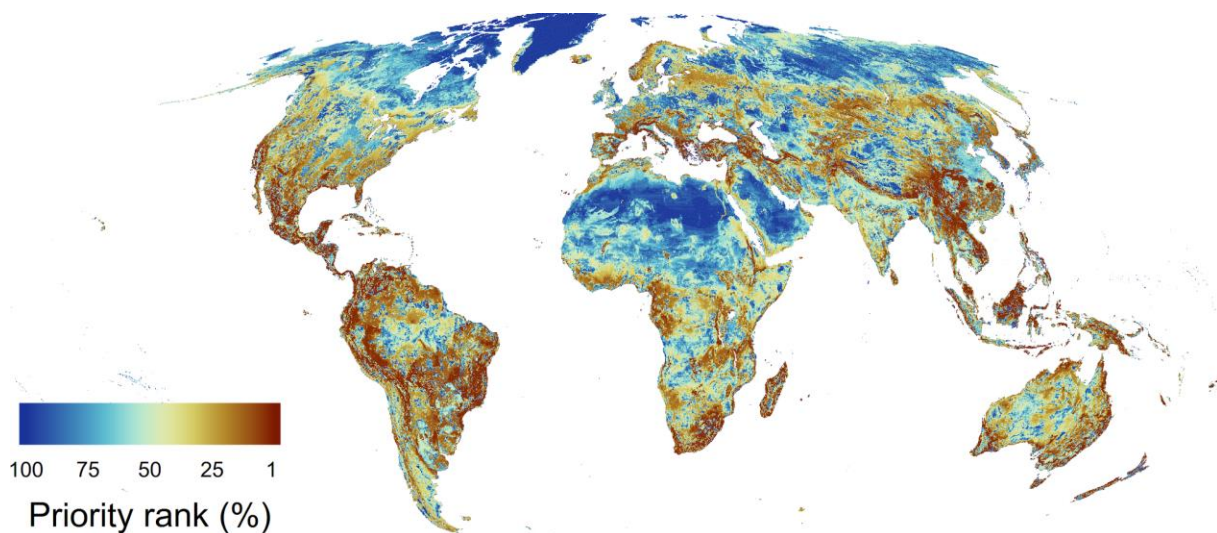
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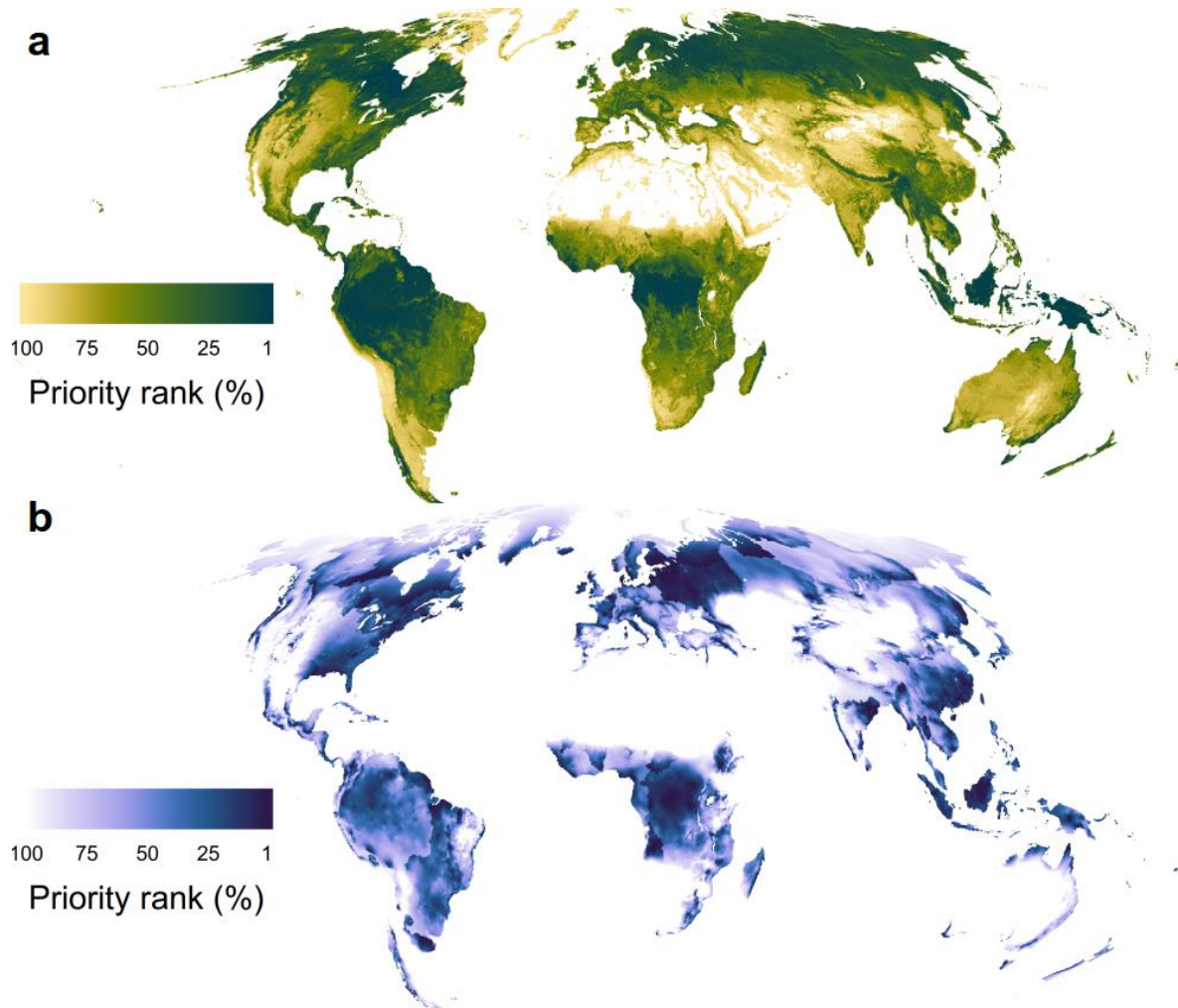
**SI Fig. 1: Uncertainty in ranks of areas of importance for biodiversity, carbon and water.** Calculated as coefficient of variation across optimal solutions with different representative sets. Expressed as percentage with lower values indicating higher precision of ranks. Map can be interpreted as overall confidence in the mapped ranks (Fig. 1), given existing biases in species range data. Map is at 10 km resolution in Mollweide projection.



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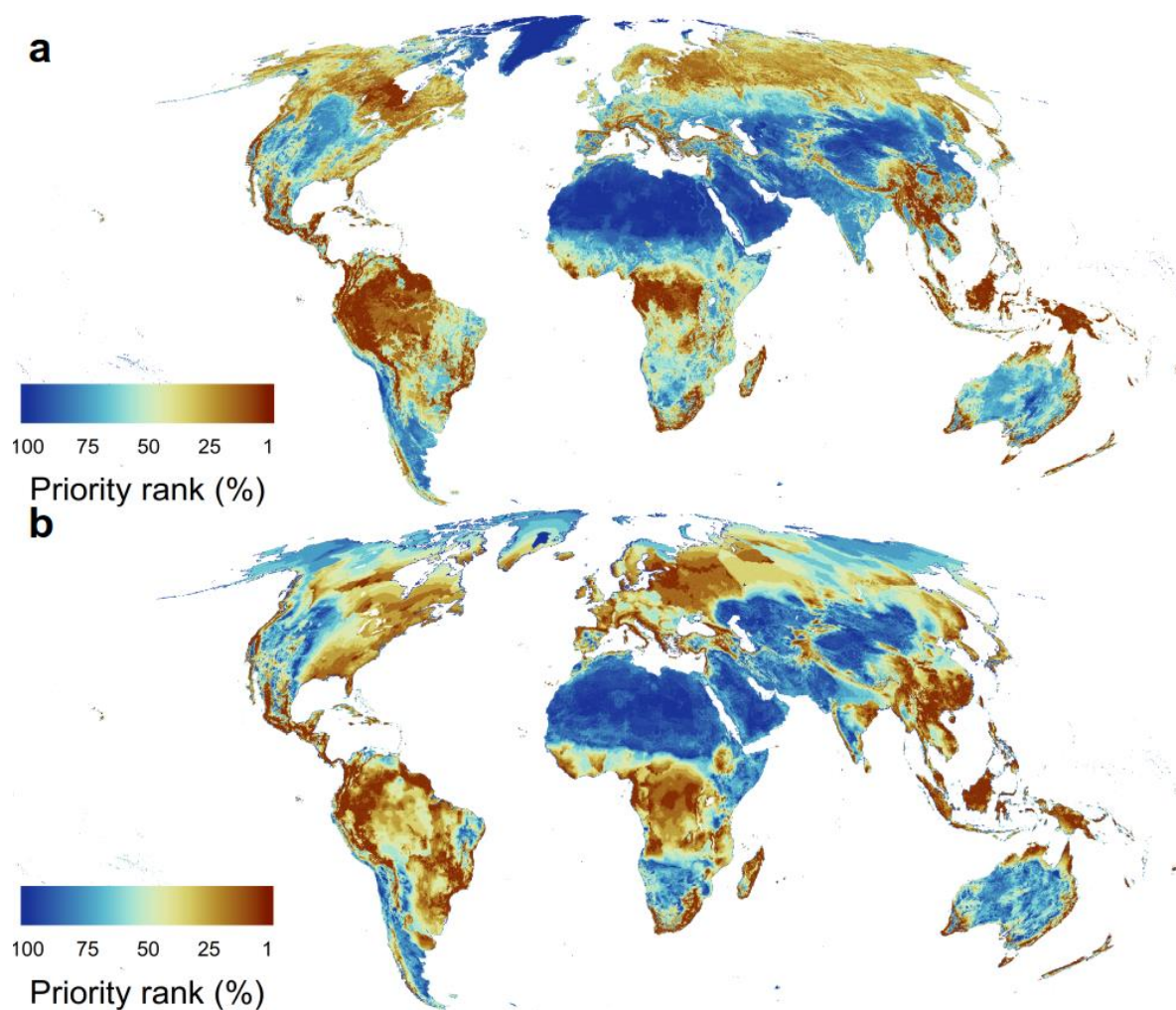
**SI Fig. 2: Global areas of importance for biodiversity only.** Ranked hierarchical maps by the most (1-10%) and least important areas (90-100%) to conserve all of biodiversity globally. Map is at 10 km resolution in Mollweide projection.

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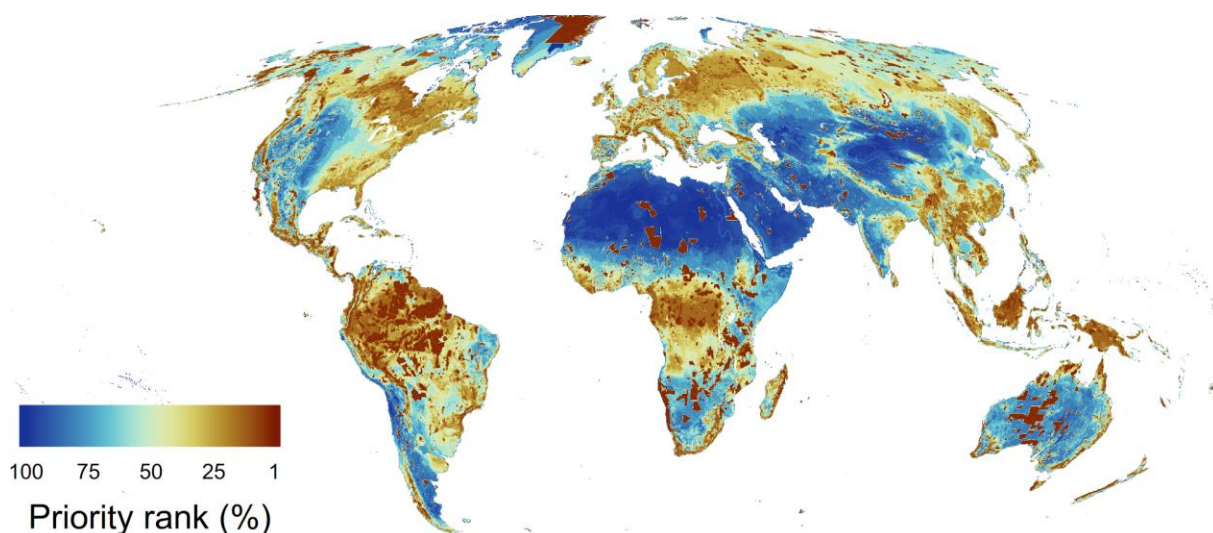
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**SI Fig. 3: Global areas of importance for carbon and water.** Normalized ranking for carbon (a) and water (b) presented as the most (1-10%) and least important areas (90-100%) to conserve globally. Map is at 10 km resolution in Mollweide projection.

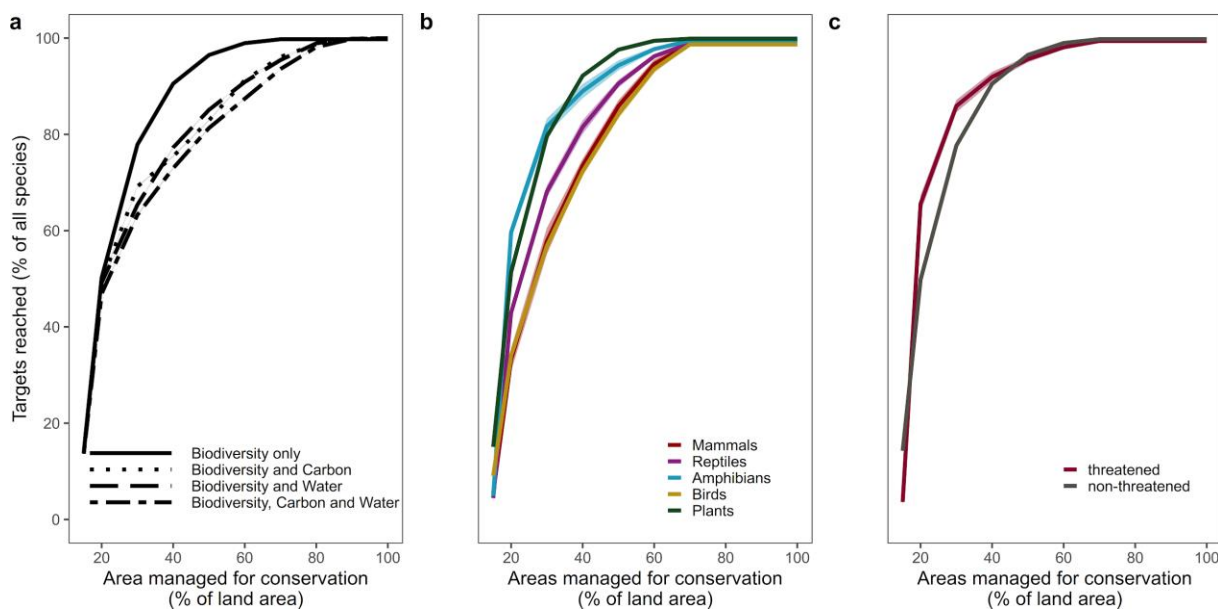


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**SI Fig. 4: Global areas of importance for biodiversity and carbon or biodiversity and water.** Showing an optimization across 10 representative sets for either (a) biodiversity and carbon or (b) biodiversity and water. All assets were jointly optimized and ranked hierarchical by the most (1-10%) and least important areas (90-100%) to conserve globally. Map is at 10 km resolution in Mollweide projection.



**SI Fig. 5: Global areas of importance for biodiversity, carbon and water considering current protected areas.** All assets were jointly optimized and ranked hierarchical by the most (1-10%) and least important areas (90-100%) to conserve globally. The fraction of grid cells currently managed for conservation (<https://www.protectedplanet.net>) are considered to be part of the most important areas. Map is at 10 km resolution in Mollweide projection.

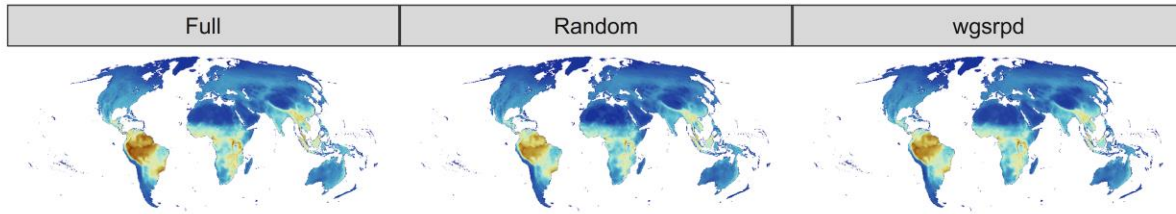


**SI Fig. 6: Accumulation curves showing how the number of species targets met increases with amount of land optimally allocated to conservation considering current protected areas.** Shows the amount of land necessary for all assets to reach all persistence targets, defined as the amount of area needed for a species to be considered at reduced risk of extinction (see Methods). Uncertainty bands (~0.1% around the mean) show the standard deviation among representative sets. Estimates shown for species (a) overall and split by additional number of assets, (b) by taxonomic group, and (c) by current IUCN assessment of threat.

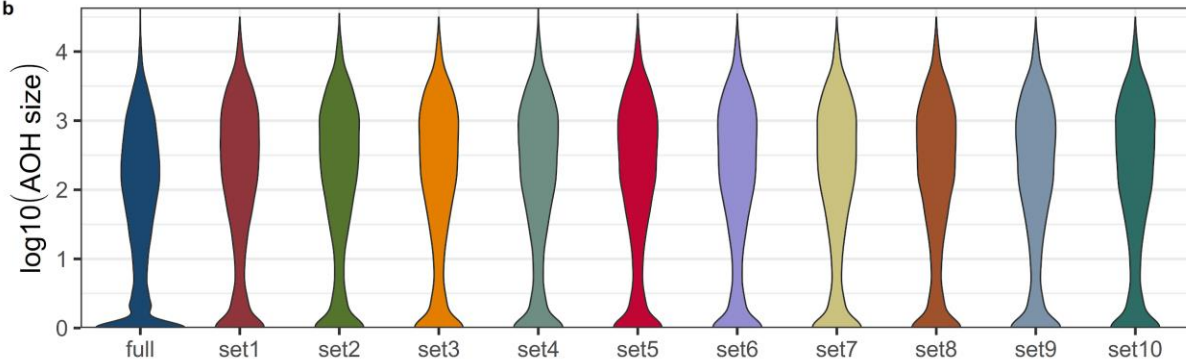


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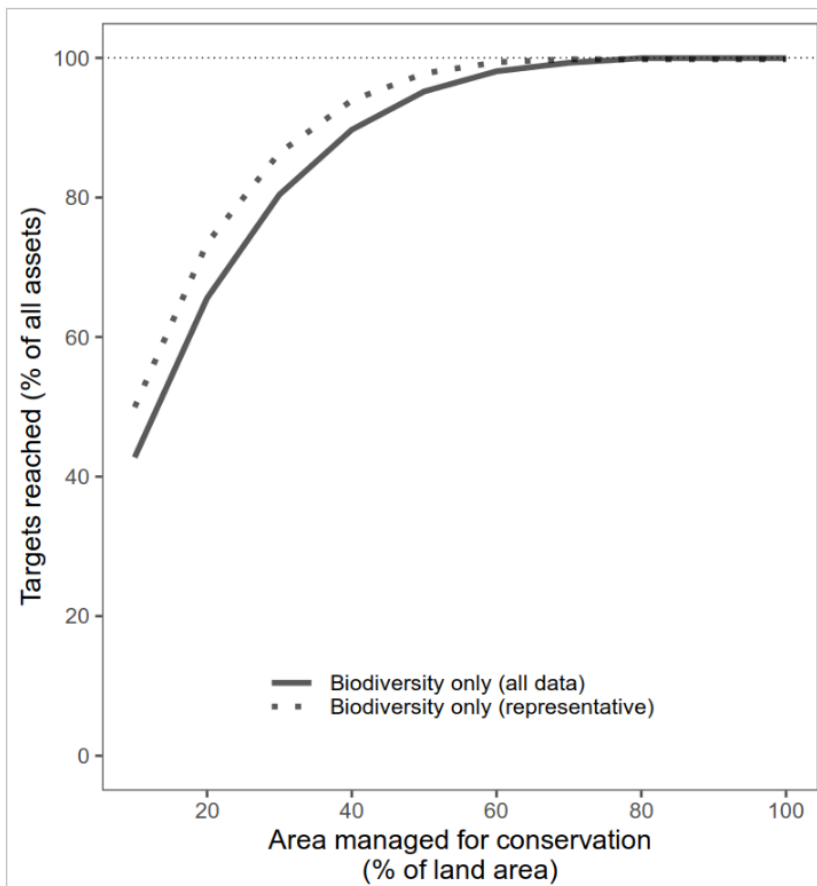
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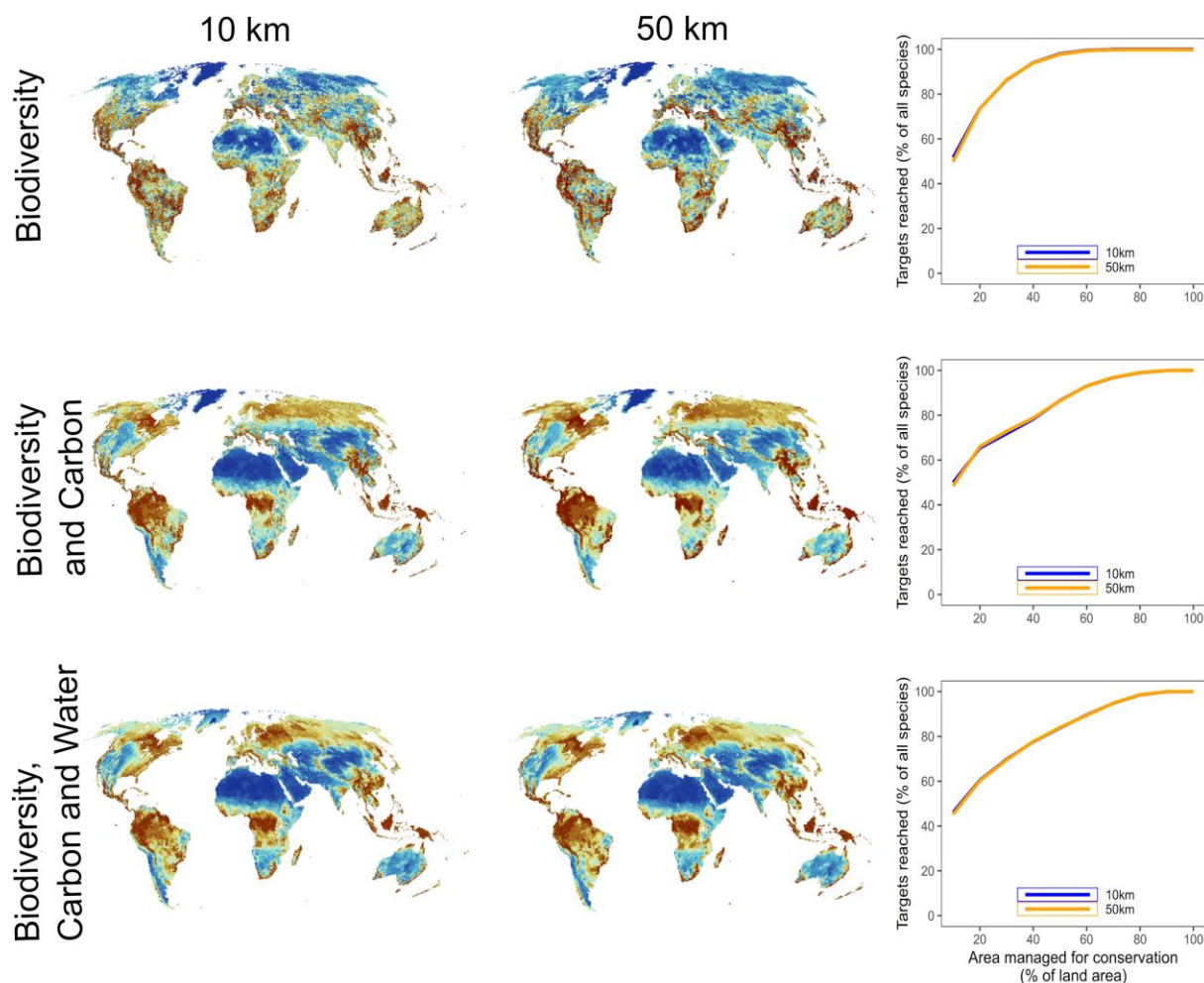
**SI Fig. 7: Comparison of representative sets spatially and in range size distributions.**

Compared to a full dataset, both subsampling at random and per WGSRPD region produces similar patterns in space and species area-size distributions. (a) Spatial map in Mollweide projection showing aggregated richness layers of all vertebrate species for the full dataset, a random sample and a representative sample by WGSRPD level 2 regions, (b) Shows the log10-transformed Area of Habitat (AOH) of all species in the full dataset (dark blue) compared to representative subsets of species (other colours).



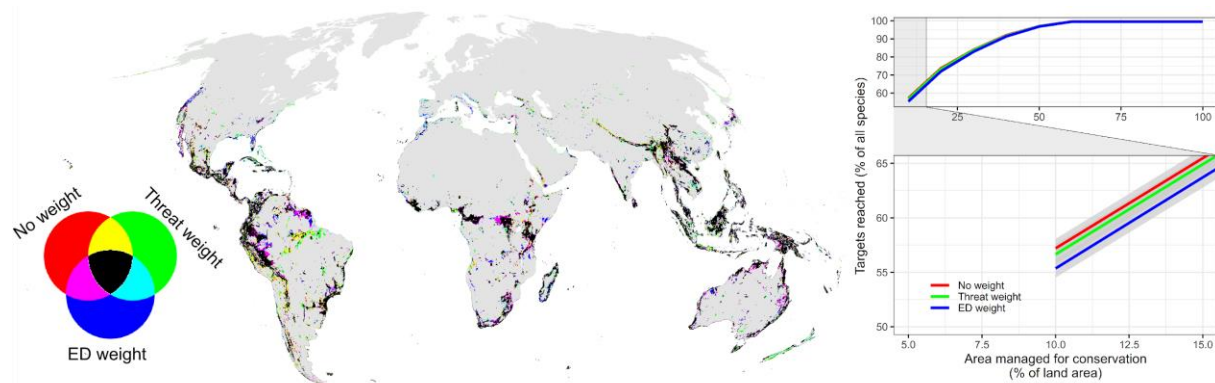
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**SI Fig. 8: Accumulation curves showing how the number of species targets met increases with amount of land optimally allocated to conservation.** Estimates shown for representative subsets (dotted line) and for all species included (solid line).



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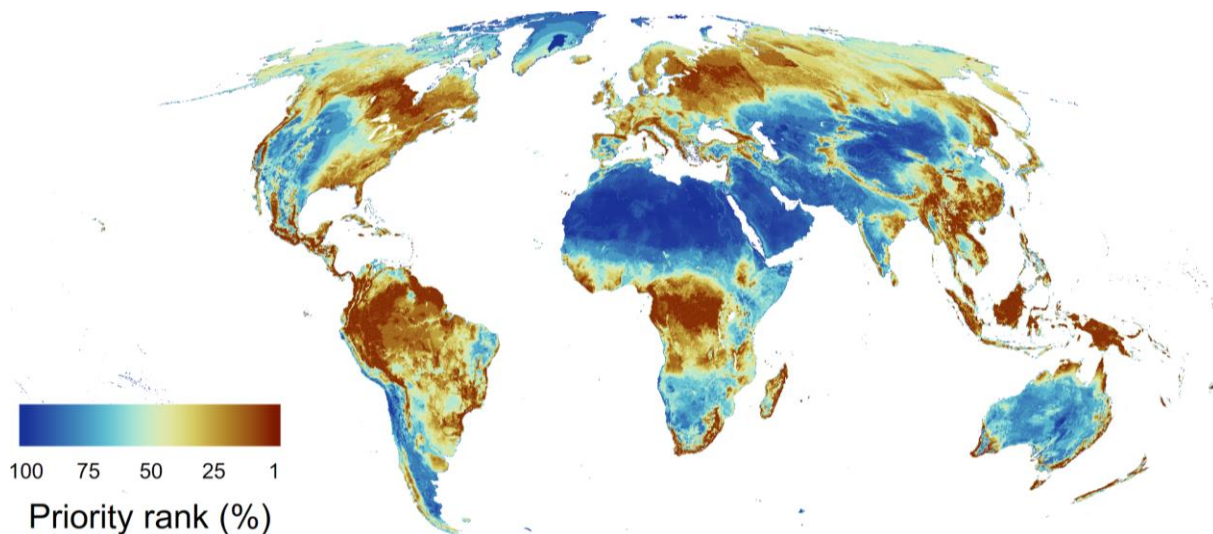
**SI Fig. 9: Comparison of global areas of importance at 10 km and 50 km areas.** Comparisons in variants of areas of importance for biodiversity only; biodiversity and carbon; and biodiversity, carbon and water. Inset graphs show how the number of species targets met increases with amount of land optimally allocated to conservation for both 10 km (blue) and 50 km (orange).



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**SI Fig. 10: Difference in the top-ranked 10% solution for varying species weights.** For each biodiversity feature a weight was assigned equating to either no differential weight (red), current

1060 threat category (green) or evolutionary distinctiveness (ED) (blue). Comparison was made only  
 1061 for species with data on both threat category and evolutionary distinctiveness . Grid cells coloured  
 1062 in black were selected in all three solutions. Map in Mollweide projection at 10 km resolution. The  
 1063 line plot shows the amount of land necessary for all species to reach all persistence targets, defined  
 1064 as the amount of area needed for a species to improve in conservation status (see Methods). Shown  
 1065 for either no weight (red), species weighted by threat status (green) and weighted by evolutionary  
 1066 distinctiveness (blue). The inset zoom highlights the difference among solutions at a budget of  
 1067 10% terrestrial land area. The confidence bounds of accumulation curves indicate the uncertainty  
 1068 among representative sets.  
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1071 **SI Fig. 11: Global areas of importance for terrestrial biodiversity, carbon and water without**  
 1072 **biome splits.** All assets were jointly optimized with equal weighting and ranked hierarchical by  
 1073 the most (1-10%) and least (90-100%) important areas to conserve globally. The map is at 10 km  
 1074 resolution in Mollweide projection.  
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1077 **SI Table 1: List of data sources included in the analysis.** Shown is the source, taxonomic  
 1078 group and number of species ranges from that source. For the analysis we preferentially used  
 1079 species range data from IUCN and Birdlife International. Subsequently we relied on GARD,  
 1080 Kew and BGCI data and used BIEN estimates of species ranges for all other plant species not  
 1081 already included. Details on data preparation can be found in the methods and supporting  
 1082 information.

Data source	Taxonomic group	Total number of species
IUCN Mammal ranges	Mammals	5,685
IUCN Amphibian ranges	Amphibians	6,660
Birdlife International	Birds	10,953
IUCN Reptiles	Reptiles	6,830
GARD Reptiles	Reptiles	3,755

IUCN Plants	Plants	8,172
IUCN Plants (new alpha hulls)	Plants	4,090
BGCI Plants (new alpha hulls)	Plants	4,571
BIEN Plant SDMs	Plants	105,336
BIEN Plant Rangebags	Plants	31,634
BIEN Plant Grid cells	Plants	40,151

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**SI Table 2: Problem variants created as part of the analyses.**

<uploaded separately>

1089 **Extended acknowledgements**

1090 This study has benefited from data made available through a number of providers and networks.  
1091 We would like to thank the IUCN Red List GIS Unit and Birdlife International for making  
1092 vertebrate and plant species ranges available for scientific research. We thank the IUCN redlist  
1093 and all species assessors globally for making habitat preference data available  
1094 (<https://iucnredlist.org>). We thank Rikki Gumps and Claudia Gray for pointing us to the latest  
1095 EDGE data (<https://www.edgeofexistence.org/edge-lists/>). We thank BGCI for making available  
1096 up-to-date threat assessments of plant species via ‘threat search’  
1097 ([https://tools.bgci.org/threat\\_search.php](https://tools.bgci.org/threat_search.php)) and Royal Botanic Gardens, Kew for creating and  
1098 making available the Global Plants of The World database ([www.plantsoftheworldonline.org/](http://www.plantsoftheworldonline.org/)).

1099 We specifically thank Manaaki Whenua – Landcare Research and the New Zealand  
1100 National Herbarium Network for making data available from the New Zealand National  
1101 Vegetation Survey databank (NVS, <https://nvs.landcareresearch.co.nz/>) and the New Zealand  
1102 Virtual Herbarium Network (NZVH). We thank iNaturalist for support in raising awareness and  
1103 systematically collecting further data for countries with few plant occurrence records in a dedicated  
1104 project (<https://www.inaturalist.org/projects/naturemap-plants>).

1105 We thank all the 1076 data contributors to BIEN. This includes RAINBIO, TEAM, The  
1106 Royal Botanical Garden of Sydney, Australia, and NeoTropTree. Plot data within BIEN are from  
1107 the CVS, NVS, SALVIAS, VEGBANK, CTFS, FIA, MADIDI, and TEAM data networks and  
1108 datasets (<http://bien.nceas.ucsb.edu/bien/data-contributors/all>). We acknowledge the herbaria that  
1109 contributed data to BIEN: HA, FCO, DUKE, MFU, UNEX, VDB, ASDM, AMD, BPI, BRI, BRM,  
1110 CLF, CNPO, L, LPB, AD, A, TAES, FEN, FHO, ANSM, ASU, B, BCMEX, RAS, RB, TRH,  
1111 AAH, ACOR, UI, AK, CAS, ALCB, AKPM, EA, AAU, ALTA, ALU, AMES, AMNH, AMO,  
1112 CHAPA, GH, ANGU, ANSP, ARAN, AS, CICY, BAI, CIMI, AUT, BA, BAA, BAB, CMMEX,  
1113 BACP, BAF, BAJ, BAL, COCA, CODAGEM, BARC, BAS, BBS, BC, BCN, BCRU, BEREA,  
1114 BG, BH, BIO, BISH, SEV, BLA, BM, BOCH, MJG, BOL, CVRD, BOLV, BONN, DAV, BOUM,  
1115 BR, DES, BREM, BRLU, BSB, BUT, C, DS, CALI, CAN, CANB, CAY, EBUM, CBM, CEN,  
1116 CEPEC, CESJ, CHR, ENCB, CIIDIR, CINC, CLEMS, F, COA,  
1117 COAH,FCME,COFC,CP,COL,COLO,CONC,CORD,CPAP, CPUN, CR, CRAI, FURB, CU, G,

1118 CRP, CS, CSU, CTES, CTESN, CUZ, DAO, HB, DBN, DLF, DNA, DR, DUSS, E, HUA, EAC,  
1119 EIF, EIU, GES, GI, GLM, GMNHJ, K, GOET, GUA, EMMA, HUAZ, ERA, ESA, FAA, FAU,  
1120 FB, UVIC, FI, GZU, H, FLAS, FLOR, HCIB, FR, FTG, FUEL, GB, HNT, GDA, HPL, GENT,  
1121 HUAA, HUJ, CGE, HAL, HAM, IAC, HAMAB, HAO, HAS, IB, HASU, HBG, IBUG, HBR,  
1122 HEID, IEB, HIP, IBGE, ICEL, ICN, ILL, SF, HO, HRCB, HRP, HSS, HU, HUAL, HUEFS,  
1123 HUEM, HUFU, HUSA, HUT, IAA, HXBH, HYO, IAN, ILLS, HAC, IPRN, IMSSM, FCQ, ABH,  
1124 INEGI, INIF, BAFC, BBB, INPA, IPA, NAS, INB, INM, MW, EAN, IZTA, ISKW, ISC, ISL,  
1125 GAT, JEPS, IBSC, UCSB, ISTC, ISU, IZAC, JACA, JBAG, JE, SD, JUA, JYV, KIEL, ECON,  
1126 KSC, TOYA, MPN, USF, TALL, RELC, CATA, AQP, KMN, KMNH, KOELN, KOR, FRU,  
1127 KPM, KSTC, LAGU, TRTE, KSU, UESC, GRA, IBK, KTU, ACAD, MISSA, KU, PSU, KYO,  
1128 LA, LOMA, LW, SUU, UNITEC, TASH, NAC, UBC, IEA, GMDRC, LD, M, LE, LEB, LIL,  
1129 LINN, AV, HUCP, QFA, LISE, MBML, NM, MT, FAUC, MACF, CATIE, LTB, LISI, LISU,  
1130 MEXU, LL, LOJA, LP, LPAG, MGC, LPD, LPS, IRVC, MICH, JOTR, LSU, LBG, WOLL, LTR,  
1131 MNHN, CDBI, LYJB, MOL, DBG, AWH, NH, HSC, LMS, MELU, NZFRI, MA, UU, MU,  
1132 CSUSB, MAF, MAK, MB, KUN, MARY, MASS, MBK, MBM, UCSC, UCS, JBGP, DSM, OBI,  
1133 BESA, LSUM, FULD, MCNS, ICESI, MEL, MEN, TUB, MERL, CGMS, MFA, FSU, MG, HIB,  
1134 MIL, DPU, TRT, BABY, ETH, YAMA, SCFS, SACT, ER, JCT, JROH, SBBG, SAV, PDD, MIN,  
1135 SJSU, MMMN, PAMP, MNHM, OS, SDSU, BOTU, OXF, P, MOR, POM, MPU, MPUC, MSB,  
1136 MSC, CANU, SFV, RSA, CNS, WIN, MSUN, CIB, MUR, MTMG, VIT, MUB, MVFA, SLPM,  
1137 MVFQ, PGM, MVJB, MVM, MY, PASA, N, UCMM, HGM, TAM, BOON, UFS, MARS, CMM,  
1138 NA, NU, UADY, UAMIZ, UC, NE, NHM, NHMC, NHT, UFMA, NLH, UFRJ, UFRN, ULS,  
1139 UMO, UNL, UNM, US, NMB, NMNL, USP, NMR, NMSU, WIS, NSPM, XAL, NSW, NT, ZMT,  
1140 BRIT, MO, NCU, NY, TEX, U, UNCC, NUM, O, CHSC, LINC, CHAS, ODU, CDA, OSA, OSC,  
1141 OSH, OULU, OWU, PACA, PAR, UPS, PE, PEL, SGO, PEUFR, PFC, PH, PKDC, SI, PLAT,  
1142 PMA, PORT, PR, QM, PRC, TRA, PRE, PY, QCA, TROM, QCNE, QRS, UH, QUE, R, SAM,  
1143 RBR, REG, RFA, RIOC, RM, RNG, RYU, S, SALA, SANT, SAPS, SASK, SBT, SEL, SIU,  
1144 SJRP, SMDB, SMF, SNM, SOM, SP, SRFA, SPF, SPSF, SQF, STL, STU, SVG, TAI, TAIF,  
1145 TAMU, TAN, TEF, TENN, TEPB, TFC, TI, TKPM, TNS, TO, TU, UAM, UB, UCR, UEC, UFG,  
1146 UFMT, UFP, UGDA, UJAT, ULM, UME, UNA, UNB, UNR, UNSL, UPCB, UPEI, UPNA,  
1147 USAS, USJ, USM, USNC, USZ, UT, UTC, UTEP, UWO, V, VAL, VALD, VEN, VMSL, VT,  
1148 W, WAG, WAT, WII, WELT, WFU, WMNH, WS, WTU, WU, Z, ZSS, ZT, CUVC, LZ, AAS,  
1149 AFS, BHCB, CHAM, FM, PERTH, SAN.

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